APPROVED FOR PUBLIC RELEASE

SCANNED NOV 11 1996

SCANNED NOV 11 1996

VERIFIED UNCLASSIFIED
LMR 6-11-79

~~CIRCULATION LIMITED~~

~~To be opened by addressee or other specially authorized persons.~~

~~To be circulated in sealed envelope or hand-carried by specially authorized persons.~~

~~List to be kept of persons having access to contents.~~

~~To be returned to Los Alamos when no longer required.~~

~~Form 403—1M—[illegible]~~

DECLAS
SIFIED

UNCLASSIFIED
[redacted]

LA-550

[redacted]

April 9, 1946 Series B C.3 This document contains 84 pages

CROSS-ROADS HANDBOOK OF EXPLOSION PHENOMENA

Compiled By:

S. T. Cohen
J. O. Hirschfelder
M. Hull
J. L. Magee

with the aid of K. Fuchs, M. P. O'Brien, W. G. Penney, R. Revelle, V. Weisskopf and others.

Classification changed to UNCLASSIFIED
by authority of the U. S. Atomic Energy Commission,
Per Ltr. J. H. Kahn, Declass. Br. OR 9-4-62
By REPORT LIBRARY Dan Dora 9-26-62

~~CIRCULATION~~
~~LIMITED~~

PUBLICLY RELEASABLE
LANL Classification Group
MAR 12 1996

VERIFIED UNCLASSIFIED
MAR 12 1996

This document contains information affecting the national [illegible] the United States within the meaning [illegible] 31 and 32, its [illegible] contents in any manner [illegible] by law.

UNCLASSIFIED

CHECKLIST FOR IA-550
CROSSROADS HANDBOOK

Please list all additions to IA-550 on this checklist sheet.

Contents	pages	figures	Comments
Table of Contents	1		
I-1	3		
I-2	4		
I-3	9	4	
I-4	16		
II-1	1	1	
II-2	1		
II-3	1		
II-4	2		
II-5	5		
II-6	1	1	
IV-1	6		
VI-1	4	1	
VIII-1	3		
X-1	4		
X-1A	2		
No. 1015 (Cont'd)	8		
No. 1015	5		

[redacted]

CROSS-ROADS HANDBOOK OF EXPLOSION PHENOMENA

Prepared by Los Alamos Group B-15

Table of Contents

Reports on the above topics will be submitted from time to time. They will bear a Roman numeral corresponding to the section to which they belong and an Arabic numeral for additional designation. The material presented in these reports will be of a tentative nature and will be subject to revision and retraction on the basis of subsequent information.

[redacted]

[redacted]

REPORT 1-1

Preliminary Description of Test A

1. Introduction

In this report a brief description of an idealized atomic explosion of 20,000 tons TNT equivalent[1] is given. The explosion takes place 200 yards above a rigid medium; the wave motion of the water is neglected for the present. The effect of water vapor on the expansion and rise of the "ball of fire" is neglected. All numerical values given are highly tentative.

The purpose of this report is to present for orientation a time schedule, a set of shock pressures and radiation intensities. Damage and contamination problems are not discussed.

2. Description of nuclear explosion

When the energy from a nuclear explosion reaches the air surrounding the bomb, thermal radiation presents the fastest mechanism of energy transfer. Thus there follows a period of "radiation expansion." This period is characterized by having the air heated to a high temperature by radiation before it is set into motion by hydrodynamical signals from the outward-moving material from the center. The radiation expansion is always diffusive and never approaches very closely the velocity of light: for a twenty-thousand-ton TNT equivalent yield the initial velocity will be slightly less than 10^9 cm/sec. As more air is taken in, the temperature and velocity drop. When the velocity drops to about 4×10^6 cm/sec, a strong shock wave develops. For a 20-kilo-ton gadget, the strong shock starts at a radius of about 15 yards. At this time the temperature is down to about 100,000°.

[redacted]

---

[1] A ton of TNT is, by definition, 4.18×10^{16} ergs. This is also 3.09×10^9 ft-lbs., 10^9 gram calories, or 4.18×10^9 watt-seconds.

[redacted]

During the first phase of the strong shock period, radiation comes from the shock front; this continues until the shock radius is about 125 yards. At this time the shock pressure is about 40 atmospheres and the temperature about 2100° K. At this point the radiating front separates and lags behind the shock front. The time is now about 23 milliseconds. The actual amount of radiant energy which has been given off up until this time is rather small, although the period of high surface brightness for the radiating front is passed. At about 23 milliseconds the brightness goes through a minimum, then ? it grows somewhat brighter and remains at the order of a few times solar brightness for a period of ten to fifteen seconds for an observer at 10,000 yards. Most of the radiation is given off in the period after 23 milliseconds.

During most of the shock history, a shock front transparent to the radiation from the hot core expands into the atmosphere.[2] At 71 milliseconds the water is struck, and a shock wave is reflected back into the air. Since there is as yet no suction phase present, the reflected shock will rapidly unite with the original shock all over the (hemispherical) front. This will strengthen the shock and make it correspond to something like twice the energy yield. This phenomenon is familiar from ordinary charges fired near the ground.

The ball of fire expands to about 275 yards radius at one second and remains bright for about ten seconds. During this time it is growing larger by mixing with the cooler air surrounding it, and rising at a rate of about 30 yards per second. At the end of the first minute the ball has expanded to a radius of about 850 yards and risen to a height of a mile. The shock wave has

---

[2] For air of high humidity there is the possibility of a "cloud chamber effect" in which condensation of water will occur in the section phase of the shock wave. In this case the light from the interior will be strongly scattered in the fog and the shock front will take on the appearance of a tremendous lamp globe.

[redacted]

[redacted]

reached a radius of about 24,000 yards, and its pressure dropped to less than 0.1 psi. The cloud continues rising at an always decreasing rate until it reaches the inversion layer at 25000 ft. in something over t minutes. There it starts to mushroom out but succeeds in pushing up a narrow column through the inversion up to a height of some 60 to 70,000 feet in a time of over 30 minutes where the cloud finally mushrooms out. The part of the cloud below 25000 feet will drift to the southwest and the part above that will drift eastward.

Time schedule for Test A.

A number of events have been selected for the purpose of giving a complete time schedule for the explosion. The table is self-explanatory.

[redacted]

[redacted]

B-15 REPORT I-2

TIME SCHEDULE FOR TEST A

by J. O. Hirschfelder and J. L. Magee

In this table we assume that the energy equivalent of 20,000 tons TNT is liberated and the bomb explodes at a height of 200 yds. We use the following symbols:

R_{shock} = radius of shock front.

D_{shock} = horizontal distance of shock front from a point directly beneath the explosion along the water surface.

T_{shock} = temperature of shock front.

Θ = visible illumination intensity measured in suns (1.94 cal/cm^2/minute) at a point 10,000 yds from the explosion.

P_{shock} = shock overpressure in either atmospheres or pounds per square inch.

V_{shock} = shock velocity

[redacted]

[redacted]

1. t = -48.7 sec, Bomb dropped from 30,000 ft.

Altitude at a horizontal distance of 16,500 ft from the target (assuming that the plane is flying at a true speed of 300 mph)

2. t = -.115 millisec, Bomb is detonated

3. t = 0, Nuclear explosion takes place.

The highest temperature reached is 60,000,000°K.

4. t = +.005 millisec, Shock wave and visible radiation reaches air.

The shock pressure is then 30,000,000 atm. and 800,000°K

5. t = .069 millisec, Radiation rushes out.

Temperature drops and Ball of Fire falls behind the shock front (only the shock front is visible in the next interval).

R_{shock} = 14.5 yds

T_{shock} = 300,000°K

P_{shock} = 20,000 atm = $P_{Ball\ Fire}$

ρ_{shock}/ρ_{air} = 9

V_{shock} = 45,000 yds/sec

φ = 50 suns at 10,000 yds

6. t = 13.8 millisec, Still see shock front.

Have started to form NO_2 ub the region of shock front which makes the front continue to radiate as a black body.

R_{shock} = 100 yds

P_{shock} = 76 atm

T_{shock} = 3300°K

V_{shock} = 3000 yds/sec

$\frac{\rho_{shock}}{\rho_{air}}$ = 9

φ = 40 suns at 10,000 yds

[redacted]

[redacted]

7. t = 23.2 millisec, The shock front becomes transparent. The radiating surface starts receding towards the ball of fire. Hence, the low value of the illumination at this time.

$R_{shock} = 125$ yds

$P_{shock} = 40$ atm

$T_{shock} = 2100°K$

$V_{shock} = 2200$ yds/sec

$$\frac{\rho_{shock}}{\rho_o} = 6.05$$

$\theta = 0.10$ sun at 10,000 yds

8. t = 70.7 milliseconds, Shock wave hits the water The shock overpressure just before the shock hits the water is only 175 psi. Immediately after the shock hits the water the shock overpressure is increased to 1000 psi due to the reflected shock wave traveling back through air which is already compressed by the incident shock (a truly strong shock in air is enhanced by a factor of 8 on reflection from a rigid surface). The temperature of the shock is correspondingly enhanced from 900°K to 2950°K. At this time the ball of fire or radiating surface is clearly distinguishable from the shock front and thirty yards behind it. The incident shock wave is not luminous but the reflected wave is; therefore, a wave of light will be seen rising from the surface of the water and pass up into the ball of fire.

$R_{shock} = 200$ yds $\theta_{shock} = 0$

Just Before the Shock hits water	Just After the Shock hits water
$P_{shock} = 175$ psi	$P_{shock} = 1000$ psi
$T_{shock} = 900°K$	$T_{shock} = 2950°K$
$V_{shock} = 1270$ yds/sec	$V_{shock} = 2880$ yds/sec

$\theta = 0.20$ suns at 10,000 yds

[redacted]

[redacted]

9. t = 0.165 seconds, Mach Stem starts to form

Up to this time the reflection of the shock from the surface of the water has been regular.

D_{shock} = 200 yds

P_{shock} = 270 psi

T_{shock} = 1100°K

V_{shock} = 1480 yds/sec

[redacted]

[redacted]

B-15 REPORT I-3

By Sgt. McAllister Hull

It has often been observed that in large explosions at sea when the humidity has been high the whole area surrounding the explosion is obscured by a hemispherical fog. This fog is formed by a Wilson cloud chamber effect. The air is first heated by the compression phase of the shock wave and is then cooled during the expansion phase of the pressure wave. If this cooling is sufficient to supersaturate the air, condensation and fog may be expected. In LA-448, F. Reines made a detailed analysis of the explosion of the U.S.S. Burke where motion picture records of the phenomenon were obtained. We have based our analysis on the results of the I.B.M. calculations scaled for a 20,000 ton explosion. Thus our results should apply directly to the Cross-Roads explosions. For explosions of some other size, both the times and the distances should be scaled as the one-third power of the explosive charge.

For a 20,000 ton explosion we conclude:

1. No fog will be formed if the humidity is less than 77% (assuming an initial temperature of 300°K or 27°C).

2. If the humidity is 100% saturated, the fog will start forming at 2.6 seconds at a distance of 1000 yards from the explosion; if the humidity is 78% saturated, the fog will start forming at 4.5 seconds at a distance of 1700 yards. Depending on the humidity, the fog will keep on forming for various lengths of time.

3. As in the case of the U.S.S. Burke, we can expect that the fog once formed will dissipate by being blown up into the rising smoke column after some 8 or 10 seconds. Although the fog is no longer stable after the suction phase of the shock has passed it takes a considerable length of time for the droplets to

[redacted]

[redacted]

evaporate.

4. The time and radius at which the fog first forms and the radius to which it grows may be used to make a crude estimate of the energy released in the explosion. It is probably not an accurate estimate since the interpretations depend critically on the exact shape of the pressure pulses.

The occurrence of a cloud chamber effect after the explosion will depend on the relative humidity of the atmosphere in the vicinity and on the change in temperature resulting from the successive compression and rarefaction due to the passing shock wave. If the peak overpressure of the shock wave is great enough the final temperature at a point will be greater than the original temperature and no cloud can form. A calculation was made of the maximum temperature change at several distances. The data were calculated from

$$\frac{\delta T}{T} = .2782 \left(\frac{po - p_{min}}{po}\right) - .1758 \left(\frac{ps - po}{po}\right)^3 ,$$

where δT is the change in temperature, T the temperature before the explosion, po the pressure in psi before the explosion, ps the shock pressure, and p_{min} the minimum pressure. The second term was derived from the shock conditions by an asymptotic expansion valid for small shock pressures (LA-165, eq. 289), and the first term arises from the adiabatic expansion after the shock wave has passed and this term is valid for pressure changes small compared to 1 atmosphere. Table I gives the values as gotten with the times of the pressure minima abstracted from IBM data. T is assumed to be 300°K, po to be 1 atmosphere. Data on distance and pressures calculated for a 20,000 ton TNT equivalent explosion from IBM data. δT is the temperature decrease.

[redacted]

12

[redacted]

TABLE I

R	$\frac{ps - po}{po}$	$\underline{po - p_{min}}$	$\frac{\delta T}{T}$	δT	t at p_{min}
271.9 yds	10 atm	0.22 atm	-175.2	-52,560° C	1.25 sec
355.8	5	.22	- 21.85	- 6,555	1.26
528.7	2	.18	- 1.350	- 405	1.73
742.9	1	.13	- .1380	- 41.4	2.03
956.5	0.62	.109	+ .0130	- 3.9	2.71
1086	0.5	.09	+ .0039	+ 1.17	2.99
1368	0.34	.071	+ .0132	+ 3.90	3.66
1949	0.2	.05	+ .0130	+ 3.96-	5.40
3235	0.1	.03	+ .0084	+ 2.5	9.15
5710	0.05	.02	+ .0057	+ 1.7	15.62

Figure 1 is a plot of δT vs. $\frac{ps - po}{po}$, and shows that for a shock overpressure of more than 7.8 psi the temperature change will be positive. For shock overpressures between 0 and 7.8 psi, cloud formation may occur. The distance at which the shock overpressure is 7.8 psi is about 1000 yds from the explosion. Zero shock o-p is infinitely distant, but is reduced to 0.36 psi (corresponding to a δT of 1°C) at about 10000 yds. For 100% relative humidity and 300°K temperature before shock, cloud formation can be expected to start at 1000 yds.

The minimum relative humidity necessary for cloud formation at a given distance from the explosion may be calculated from the δT column of Table I with a knowledge of the mixing ratios of the atmosphere at the temperatures

[redacted]

[redacted]

in question. Assume T_0 = 300°K, then at 1949 the maximum temperature drop is 3.96°C, bringing the temperature to 296.4°K. the saturation mixing ratios at these two temperatures and 1 atmosphere are 23 g/kg air and 17.9 g/kg air respectively. The minimum relative humidity for cloud formation at this distance is 17.0/23, or 77.8%. Similar calculations for the distances of interest are shown in Table II. These data are plotted in Figure 2.

TABLE II

R	δT	Mixing Ratio 300°K, 1 atm	Mixing Ratio 1 atm, $(300-\delta T)$°K	Min. Rel. Hum.
1000	0	23	23	100%
1086	1.17	↓	21	91.3
1368	3.90	↓	18	78.2
1949	3.96	↓	17.9	77.8
3235	2.52	↓	19.5	84.8
5710	1.71	↓	20.5	89.1
10000	1	↓	21.6	94

Figure 2 also shows the time at which the maximum temperature changes occur, as shown in the last column of Table I. It was found that the velocity of the shock minimum this region is about constant: 365.6 yds/sec. Thus the time-distance relation is

$$t_{sec} = .00274\ R\ yds$$

This allows a linear time scale, which is shown as a second abscissa in Fig. 2.

Since the pressure goes negative before it reaches its minimum value, and is still negative a short time beyond the minimum, the humidity-distance

[redacted]

[redacted]

PREDICTED ASCENT FOR KWAJELEIN, June 3, 1945, SURFACE SHOT

$\alpha = .1$

Mean Height of Cloud in 1000 Feet	Time (sec)	Radius (m)	Volume (m^3)	Mass (kg)	Density ($\frac{gm}{cm^3}$)	Temp (^oA)	Velocity ($\frac{m}{sec}$)
0	0	2.03×10^2	3.51×10^7	1.30×10^7	$.372 \times 10^{-3}$	600	24.4
2		2.69	8.13	6.41	.788	379	45.9
4	32.7	3.39	1.34×10^8	1.44×10^8	.883	332	34.4
6		4.10	2.89	2.59	.896	311	28.4
8	61.3	4.83	4.72	4.11	.872	300	25.5
10		5.57	7.23	6.05	.836	294	21.5
12	101	6.34	1.08×10^9	8.43	.789	288	15.7
14		7.11	1.51	1.13×10^9	.750	283	11.5
16	146	7.89	2.06	1.47	.712	279	6.97
18		8.70	2.76	1.86	.673	275	0
20	198	9.50	3.59	2.30	.640	270	
22		1.03×10^3	4.62	2.79	.604	266	
24	264	1.12	5.88	3.33	.568	262	
26		1.20	7.27	3.93	.535	258	
28	355	1.30	9.17	4.57	.500	253	
30		1.39	1.12×10^{10}	5.27	.468	248	
32	486	1.49	1.37	6.01	.436	243	
34		1.57	1.63	6.81	.411	239	
36		1.68	1.98	7.67	.387	234	

E-15-Report-1-5
To be inserted after Table II

curve is actually broader in time than is shown in the solid line of Fig. 2. To correct for this, the dotted curve is drawn in to be used with the time abscissa.

If a cloud forms as the shock wave moves out, the visibility with respect to the ball of fire will be reduced, or perhaps the ball will be totally obscured. The reduction in visibility is a function of the cloud density and of the thickness of the cloud.

The cloud density may be calculated as a function of humidity at any point, and the relation is linear. The difference between the saturation mixing ratio at the original temperature (300°K) and that at the minimum temperature reached gives the amount of water in gms/kilogram of air condensed into cloud droplets. It should be noted that these calculations are not very sensitive to changes in the original temperature; an error of 2 to 3% being introduced if the original temperature lies between 298°K and 310°K. Temperatures less than 298°K are not anticipated, but an error of not more than 5% should occur if these figures are used for temperatures as low as 283°K before the explosion.

Once the amount of water condensed is known, the cloud density is given by

$$p = (Ws_o - Ws)\ 1.177$$

, where Ws_o and Ws are the mixing ratios, and p is in gm/meter^3. Table III gives the calculated values of p at several densities for a relative humidity of 100%. Figure 4 gives the relation between relative humidity and cloud density at those distances.

TABLE III

R	$Ws_o - Ws$	ρ (R. H. 100%)
1086	2	2.35
1368	5	5.88
1949	5.1	6.00
3235	3.5	4.12
5710	2.5	2.94
10000	1.5	1.77

[redacted]

[redacted]

The reduction in visibility was assumed to be an exponential function of cloud thickness according to

$v = (e^{-kx})100$, to give v in percent of the visibility without the cloud. We assume k to be a linear function of ρ, the cloud density, and we can calculate the relationship from the one available datum: Shaw, <u>Manual of Meteorology</u>, Vol. III, p 342. This reference gives the observation that visibility was reduced to 40 meters when the cloud density was 0.87 gm/meter^3. If we assume "reduced to 40 meters" to mean that visibility was reduced to 0.1% in a 40 meter thickness of cloud of density 0.879/meter^3, k may be evaluated. Calculation gives

$$k = .01816\,\rho, \text{ if } x \text{ is in yards.}$$

Table IV gives the calculated values of x, the cloud thickness, for which visibility is reduced to 0.1% for several values of ρ.

TABLE IV

ρ	v	x
0.5	0.1%	75.9 yds
1	↓	27.9
2		19.0
3		12.7
4		9.5
5		7.6
6		6.3

In Figure 3 is plotted thickness of cloud vs visibility for the values of p noted in Table IV. Those values of p include all of those calculated as expected densities of cloud in Table III. In addition, Figure 4 has been plotted

[redacted]

[redacted]

on Figure 3 on the log-log scales. Thus from Figure 3 the cloud density to be expected at a given humidity and distance may be had, and the reduction in visibility for a given cloud thickness may be read from the density-visibility curves. An estimate of cloud thickness may be had from Figure 2 for given humidity. In any case, the cloud is opaque whenever there is any appreciable condensation.

The final question to be considered to complete the analysis of the cloud-chamber effect is that of the cloud stability. Stability with respect to evaporation need not bother us because the cloud is reasonably near saturation (not less than 77%) and evaporation will be slower than any other effect we consider.

Vertical stability, or stability with respect to vertical displacement, depends on the lapse rates within the cloud and the environment. Holmboe Dynamic Meteorology) defines the saturated lapse rate as

$$\gamma_s = \frac{R_dT + LW_s}{R_dT + (\frac{EL^2W_s + EL^2W_s{}^2\ 0.61}{T}}$$, where W_s is the

mixing ratio and the other factors are constant. R_dT is small compared to L (.08 compared to 2.5), and we may write approximately

$$\gamma_s \sim \frac{1}{EL(1 + 0.61W_s{}^2}$$, or, neglecting 1 in comparison

with $0.61W^2$ (~ 240),

$$\gamma_s \sim \frac{1}{EL(0.61W^2)}\text{ , or }\gamma_s \propto \frac{1}{W_s{}^2}\ .$$

Since the cloud was formed by condensing some of the water out of the surrounding atmosphere, the mixing ration within the cloud will be smaller than the mixing ratio of the environment which has lost none of its vapor to condensation. From the equation for the lapse rate just given, we conclude

$(\gamma_s)_{\text{cloud}} > (\gamma_s)_{\text{environment}}$, which is the

[redacted]

[redacted]

condition for vertical instability. Thus the cloud, if formed, will begin to rise from the ocean.

The wind toward the center of the explosion which occurs as the pressure there is brought back to equilibrium will tend to break up the cloud as well as to lift it upward. Also, the rising ball of hot air will tend to take the upper parts of the cloud with it. All of these factors make an estimate of the persistence of the cloud and its velocity of rise difficult. The general conclusions about stability, however, are borne out by the pictures of the explosion of the U.S.S. John Burke, where a hemispherical cloud was formed beginning at about 520 yards from the center of the explosion. This estimate of distance was made from a calculated scale placed on pictures of the explosion and is probably not particularly good. However, scaling up the explosion from 3000 to 20000 tons, the distance at which a cloud would be expected is 520 x $(\frac{20000}{3000})^{1/3}$, or about 990 yards. This is in fair agreement with the calculated minimum distance of cloud formation of 1000 yards.

From this point on, times may be scaled since time differences are known from the frame speed of the camera (16 frames/sec). The cloud from the Burke ceases growing at about 3.1 seconds after it begins to form, corresponding to a growth time of 3.1 x $(\frac{20}{3})^{1/3}$ = 5.9 seconds for the larger explosion. This corresponds to a cloud formed at about 82.5% humidity, beginning at about 1080 yards and 2.8 seconds from the center of the explosion. Note that the scaled value of the distance at which the Burke's cloud began to form is about 92% of that given above from cloud growth considerations.

[redacted]

[redacted]

The cloud formed by the Burke's explosion seemed to begin to rise as it was formed, and so began to clear the ocean when it had reached maximum growth, corresponding to a time of about 9 seconds for the 20000 ton shot. It rose to a height of 500 yards in about 2.9 seconds after growth stopped, which gives a speed of rise of about 170 yards/sec (~ 6 miles/hr). The rate of rise of the cloud depends on cloud composition, so that this figure need not be scaled if we assume the cloud compositions to be about the same.

We may conclude, then, that a cloud if formed by the nuclear explosion will begin to rise when its growth is completed, and will rise at a rate of about 6 miles per hour. Growth time can be read off Figure 2 for given humidity.

[redacted]

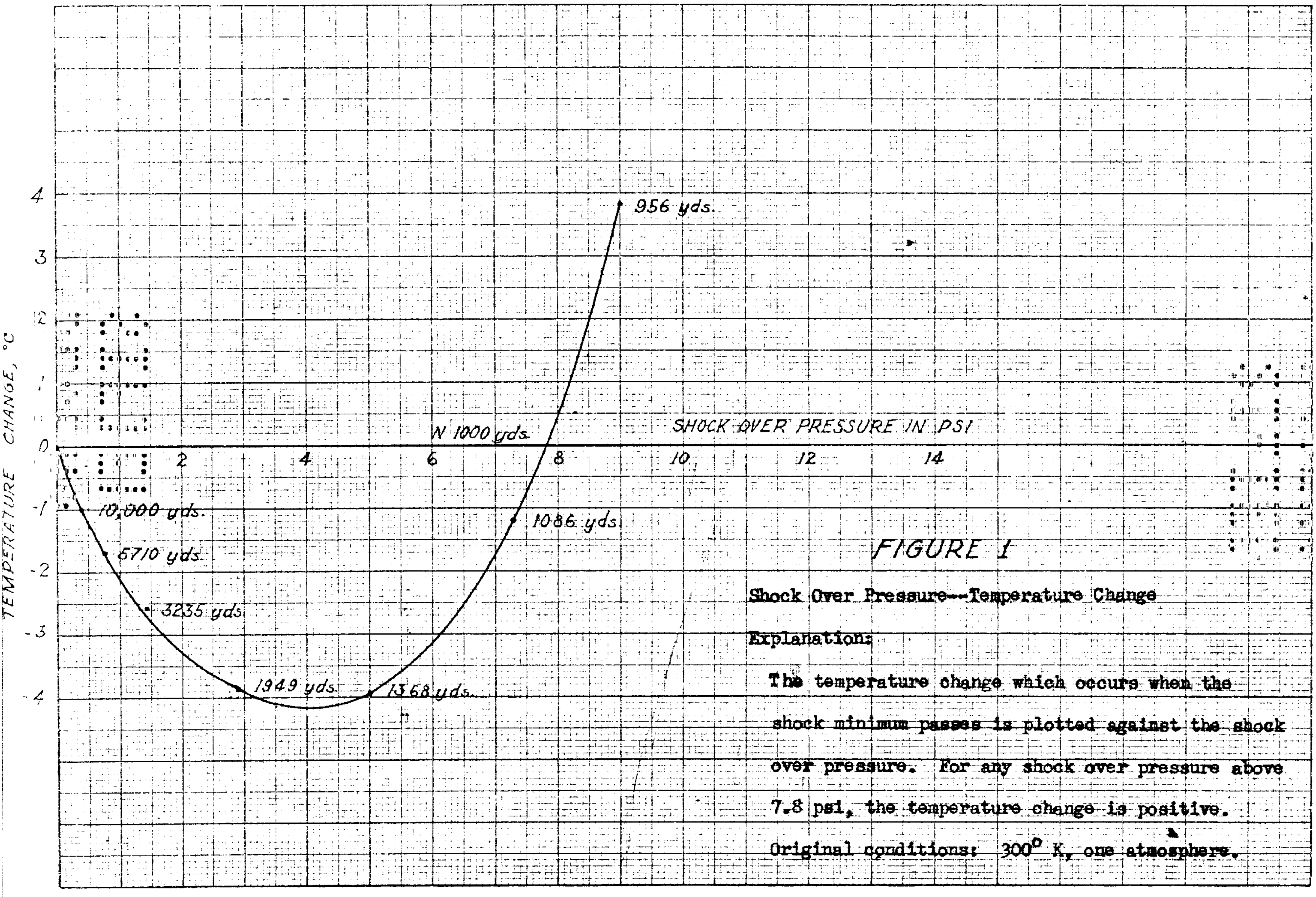


FIGURE I

Shock Over Pressure--Temperature Change

Explanation:

The temperature change which occurs when the shock minimum passes is plotted against the shock over pressure. For any shock over pressure above 7.8 psi, the temperature change is positive.

Original conditions: 300° K, one atmosphere.

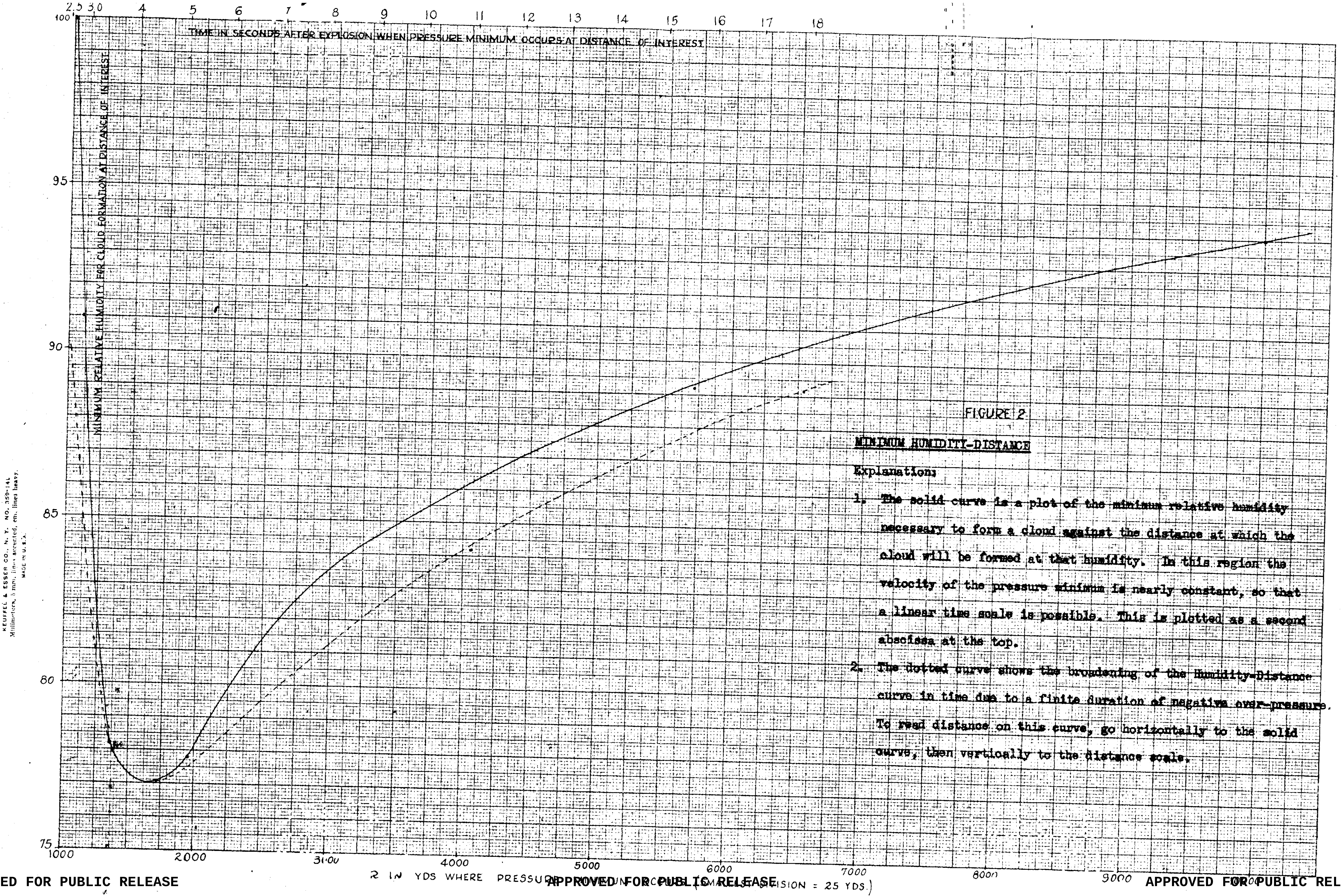


FIGURE 2

MINIMUM HUMIDITY-DISTANCE

Explanation;

1. The solid curve is a plot of the minimum relative humidity necessary to form a cloud against the distance at which the cloud will be formed at that humidity. In this region the velocity of the pressure minimum is nearly constant, so that a linear time scale is possible. This is plotted as a second abscissa at the top.
2. The dotted curve shows the broadening of the Humidity-Distance curve in time due to a finite duration of negative over-pressure. To read distance on this curve, go horizontally to the solid curve, then vertically to the distance scale.

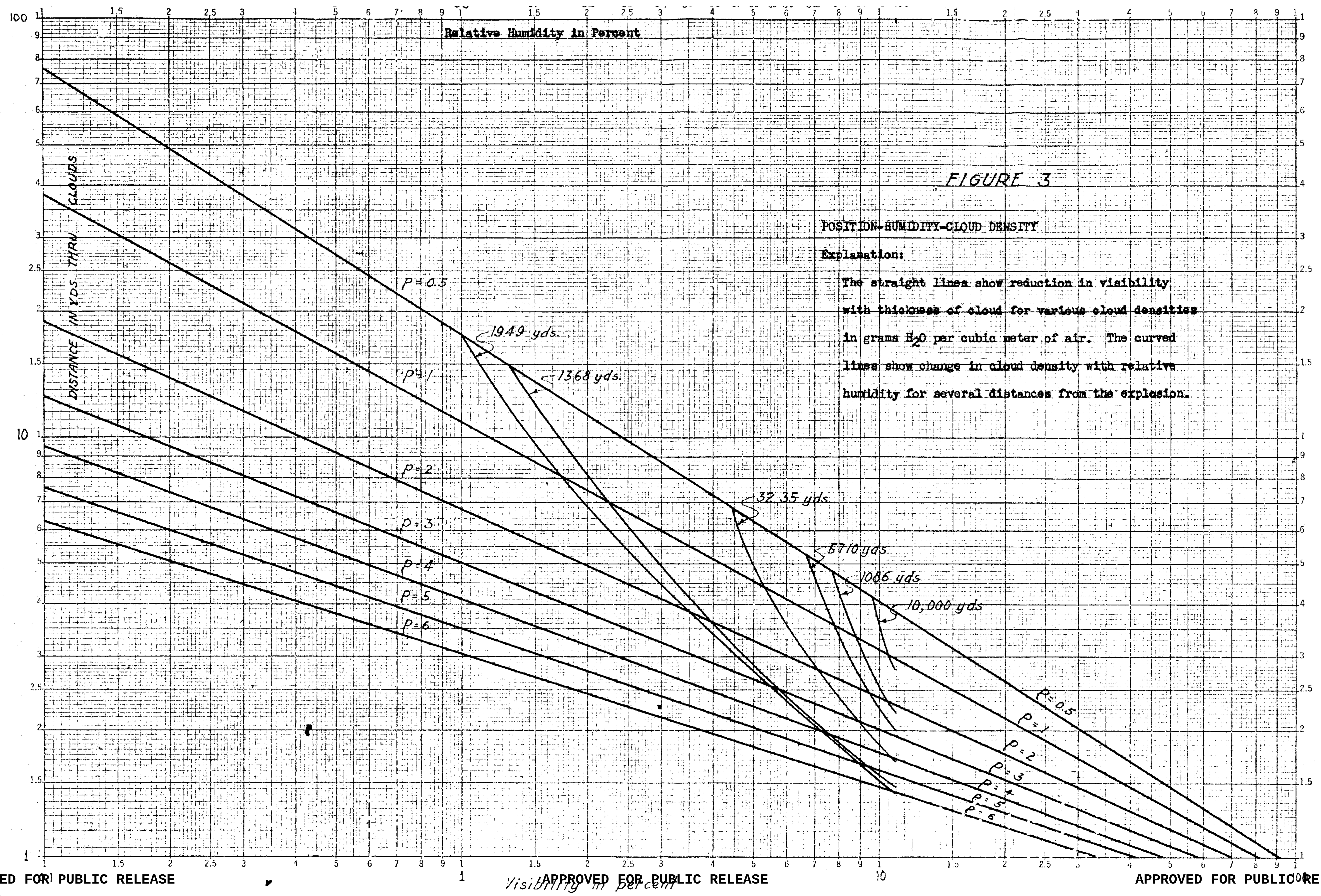


FIGURE 3

POSITION-HUMIDITY-CLOUD DENSITY

Explanation:

The straight lines show reduction in visibility with thickness of cloud for various cloud densities in grams H_2O per cubic meter of air. The curved lines show change in cloud density with relative humidity for several distances from the explosion.

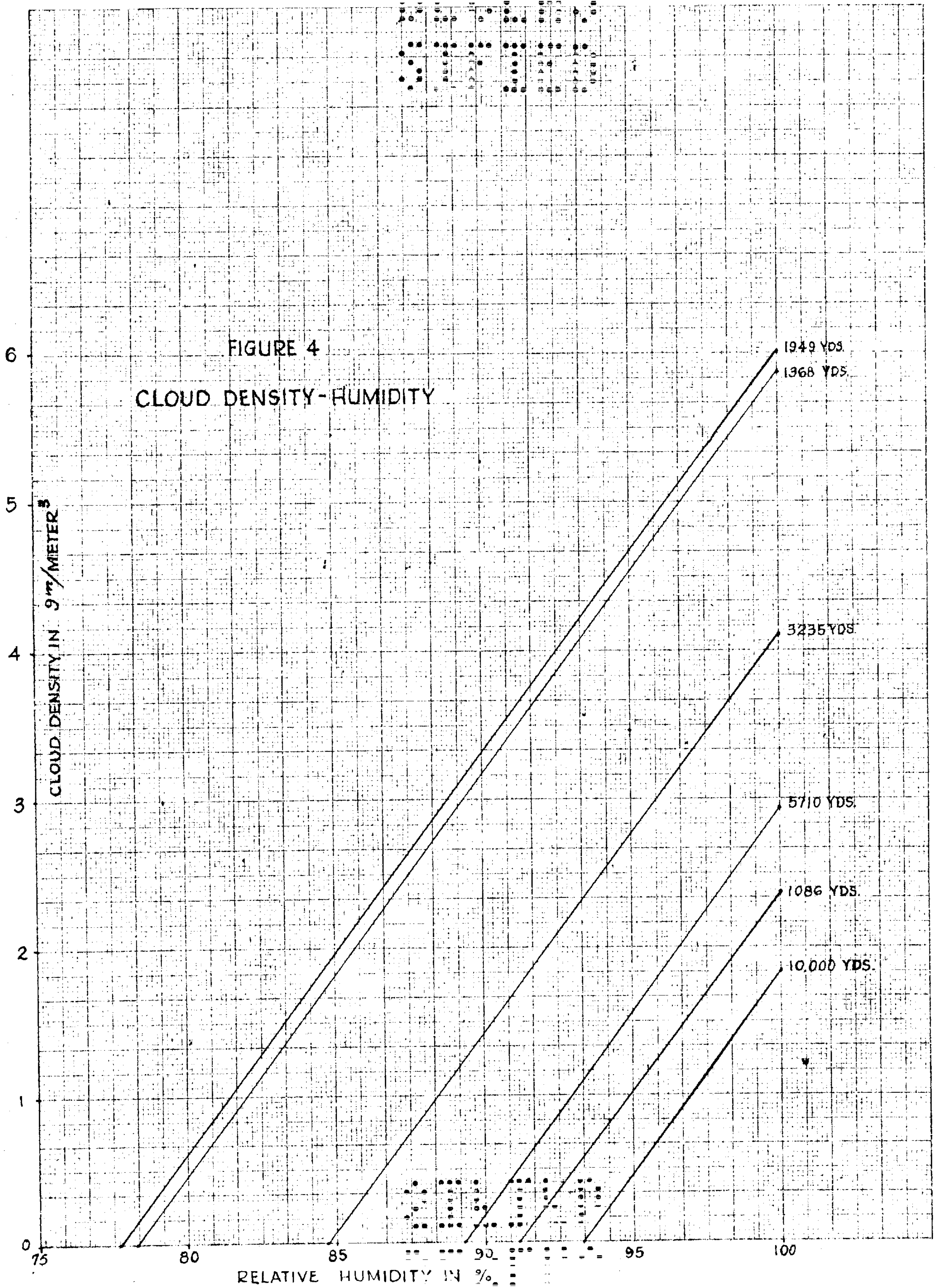


FIGURE 4

CLOUD DENSITY-HUMIDITY

[redacted]

GROUP B-15 REPORT I-4

General Description of the Radiation Produced by the Atom Bomb

I. Radiation During First Minute

There are several types of radiation given off by the atomic bomb. At the time of the explosion there are: visible and thermal radiation, γ-radiation and neutrons. The visible and thermal radiation is most dangerous to personnel at large distances: a person's skin can be raised 50°C by the ultraviolet flash of the first millisecond at a distance of 4000 yards. People may be injured by flash burns to larger distances. Gamma radiation danger extends somewhat beyond 1000 yards: at 1000 yards the γ ray dosage is 1000 Roentgen during the first minute. At 1500 to 2000 yards this radiation is not dangerous. Neutron radiation is limited to a distance of about 600 yards and certainly less than 1000 yards.

As soon as the chain reaction starts, zero time, a few hard γ rays and fast neutrons shoot out. About five microseconds later visible radiation is seen as the shock breaks through the bomb case. This lasts at rather large intensity for about ten seconds. About ten microseconds after zero a large pulse of epi-thermal neutrons reaches the air. These neutrons have a very small range and are absorbed in about two hundred meters of air. Slightly later, strong gamma radiation from the fission products starts and continues for about one minute, until the ball of fire containing the source has risen to such a height that the intensity received on the ground is negligible. During the first ten seconds or so a relatively small number of fast delayed neutrons are emitted from the fission products. They are eventually slowed down and some of them induce radioactivity in the atoms which absorb them. Their range is around six hundred yards in air.

[redacted]

24

[redacted]

A large number of beta rays are emitted during this time, but they are unimportant because their range is very short. Only the original alpha-active material of the bomb gives off alpha particles and they, too, are unimportant because of small range.

The dosage of radiation is usually expressed in Roentgen units. One Roentgen is the amount of radiation which passing through air at standard conditions would produce 2.1×10^9 ion pairs per cubic centimeter (1 e.s.u./cm^3). The physiological effects of radiation as well as the darkening of photographic plates is supposed to be cumulative so that the exposure to a weak source of radiation for a long time is equivalent to exposure to a strong source for a short time. The radiation dosage rate is expressed in Roentgen units per unit of time and the total dosage received is then the dosage rate multiplied by the exposure time. It is generally considered that a dose of 0.1 Roentgen per day can be taken every day without causing any noticeable physiological effects. However, much larger exposures can be safely taken if not repeated. For example, it will be acceptable for the monitors to receive doses of from 1 to 10 Roentgens; a dose of over 20 Roentgens is not desirable. About 25% of the people would not be affected by a dose of 100 Roentgens but another 25% of the people would become very ill. Radiation of from 500 to 1000 Roentgens usually proves fatal.

1. GAMMA RADIATION

Gamma radiation is dangerous from the standpoint of personnel, because it is penetrating and difficult to shield against. This radiation may be divided into three parts:

1. The initial burst which lasts for approximately a minute and is very intense. This is due to the fission products radiating from the ball of fire before it rises appreciably.

[redacted]

[redacted]

2. The gamma radiation from the fission products which are scattered over the water and taken up in the cloud. The rate of the fission product radiation decreases approximately inversely with time.

3. The gamma radiation from the induced radioactive materials formed by the absorption of neutrons in sea water and in the ships.

The initial burst of radiation is given off by the fission products in the ball of fire during approximately the first minute. After this time the ball of fire has risen very high and the radiation is strongly attenuated in the air before reaching the ground. If the explosion releases the amount of energy equivalent to 20,000 tons of TNT, the total dosage of gamma radiation which appears at a distance of R yards from the explosion is

$$X = \frac{400,000}{(R/500)^2} \times 10^{-(R/500)} \quad \text{Roentgen Units} \qquad (1)$$

Thus at a distance of 1,000 yards there is still a lethal dose of 1000 Roentgens. At a distance of 1,500 yards the dosage is reduced to a tolerable 44 Roentgens. The gamma radiation received is reduced by a factor of two if 3/4 inch of steel, 3/5 inch of lead, 2 inches of either concrete or aluminum, 10 inches of wood, or 5.3 inches of water are in line between the ball of fire and the point or person in question.

$\frac{7\cdot10^{10}}{5\cdot10^{2}}$

$\frac{4\cdot10^{5}\cdot10^{-2}}{4}$

$X = \frac{4\cdot10^{5}\ 10^{-14}}{196} = \frac{4}{196}\cdot10^{-9} = 4\cdot10^{-11}\,R$

2. NEUTRON EMISSION

There were a number of measurements of the neutrons emitted in the Trinity shot. At 600 meters, the total neutron flux was measured as a function of time. In agreement with the theoretical predictions of Weisskopf, only 20% were prompt neutrons; the other 80% appeared as long as 10 seconds later. The measurements of neutrons were sufficiently accurate that they sufficed to make an excellent determination of the efficiency of the bomb. From these experimental results it follows that:

$$\frac{\text{no. neutrons}}{\text{cm}^2} = 2.24 \times 10^{12} \times 10^{-(R(\text{meters})/840)^2}$$

[redacted]

[redacted]

Or:

R(meters)	100	600	1000	1500
No. Neutrons per cm^2	$2x10^{12}$	10^{11}	10^9	10^5

Since the lethal dose of neutrons is approximately 10^{11} per centimeter square, it follows that the lethal radius is around 600 meters and certainly less than 1000 meters.

3. VISIBLE AND THERMAL RADIATION

The intensity of the thermal radiation is discussed in VI-1. For an observer at 10,000 yards, the intensity will remain brighter than the sun for about 4 seconds. ? It is, however, the first flash (about 5 milliseconds in duration) which is rich in short wave length light that is expected to do most of the burning of personnel. If we assume that a person's skin has approximately the same properties as pine wood, the temperature to which skin is raised can be given by the formula (taken from VI-1):

$$\Delta T = \frac{7.45x10^8}{R^2} \,^{o}C$$

where R is the distance in yards. It is found that ΔT is about 50°C at 4000 yards.

The high skin temperatures resulting from the flash of high intensity radiation are probably as significant for injuries as the total dosages . For ultra-violet light of 2800°A × a dosage of about 10^6 $ergs/cm^2$ is necessary for production of erythema[1]. The first three milliseconds of the flash have radiating surfaces above 10,000°K and thus high intensities of ultra-violet. The total flux during this period in $ergs/cm^2$ is given by:

$$Flux = \frac{1.7 \times 10^{13}}{R^2} \; ergs/cm^2$$

× There was never any radiation shorter than 2990Å F E Geiger [see radiation report by Gill (MB)]

---

[1] S. L. Warren in B. M. Duggar Biological Effects of Radiation McGraw Hill, New York 1936

[redacted]

27

[redacted]

Radiation Time Schedule for First Minute

Time	γ-radiation	Neutrons	Thermal, visible
0--chain reaction begins	Weak intensity of prompt γ's begins, building up exponentially with time for about 2 microseconds. The total radiation for distances the order of 100 yds is negligible.	Weak intensity of prompt neutrons builds up exponentially with time for 2 microseconds. Only those which get through the bomb material without being scattered get very far. These neutrons furnish 20% of the total flux at 600 meters distance.	During this period no visible radiation is given off outside the bomb by the chain reaction directly. An extremely weak radiation due to the absorption of γ's in air is entirely negligible. 2. see radiation report by G-11 (MB) FE Geiger
5 microseconds			Shock has traversed the bomb material and energy transfer reaches air with flash of visible radiation. This radiation lasts for about ten seconds and is discussed in the Handbook VI-1.
10-20 microseconds		Neutrons which were slowed down by scattering inside the bomb begin to emerge as epithermal neutrons with about 200 ev energy. These neutrons only penetrate about 200 meters in air before absorption in nitrogen.	
50 microseconds	Radiation from fission products emerges without attenutation by the bomb materials. This radiation furnishes essentially all the dosage which is observed in the vicinity of the explosion. It lasts until the fission products are carried up in the ball of fire, about one minute.	Delayed neutrons from the fission products emerge with energy of about 600 kev. These neutrons continue to be emitted for about ten seconds. They furnich most of the intensity observed at distances as far as 600 meters.	

[redacted]

[redacted]

At about 4000 yards one gets approximately an erythema dose, 10^6 ergs/cm^2.

The combination of skin temperature increase plus large ultra-violet flux inside of 4000 yards will be damaging in all cases to exposed personnel. Beyond this point there may be cases of injury, depending upon individual sensitivity.

The infra-red dosage is probably of less importance because of its smaller intensity. The total flux received over a ten-second period of time is:

$$\text{Flux} = \frac{1.3 \times 10^{15}}{R^2} \ \text{ergs/cm}^2$$

This can also be written as:

$$\text{Flux} = \frac{2.4 \times 10^{8}}{R^2} \ \text{sun-seconds.}$$

[redacted]

II. Radiation after the First Minute

Gamma radiation is the most important physiologically after the first minute. The gamma activity is due to the decay of the fission products. The rest is due to radioactivity induced by the absorption of the neutrons emitted during the first minute.

The fission products have half-lives varying from a fraction of a second to many years. The fission products as a whole give off gamma rays at a rate which decreases approximately inversely with time. If the explosion is 20,000 tons TNT, at a time t hours after the explosion all of the fission products will produce $7.6 \times 10^{23}/t$ nominal MEV gamma rays per hour. Actually the fission products give off a wide spectrum of gamma rays with a mean energy per quantum of energy in the radiation and it suffices to think of the radiation as being made up solely of nominal 1 MEV gammas. Each MEV gamma ray makes $10^6/50$ - 20,000 ion pairs in its lifetime if we assume that each ion requires 50 ev.[*] Since the mean-free path of these gammas in air is 20,000 cms, it follows that each gamma produced one ion pair per centimeter along its path in air. Thus one Roentgen unit requires a flux of 2.1×10^9 MEV gammas per square centimeter.

The fission products soon separate into two parts - the material which remains in the cloud, and the material which has deposited on the sea and on the ships. The activity of the material in the cloud is of importance for the safety of the fliers and for the sampling by the drones. For a 20,000 ton TNT explosion it is easy to show that at the center of the cloud the intensity

---

[*] According to Weisskopf, 50 ev is the proper value to use for gamma rays in contrast to the 32 ev usually used for alpha and beta radiation. The higher value corresponds to the fact that most of the electrons produced by gamma rays are slow.

[redacted]

[redacted]

of gamma rays is

$$\frac{1830}{nt}(\rho_0/\rho_h) \text{ Roentgen units per hour} \qquad (2)$$

Here t is the time after the explosion in hours, n is the number of square miles occupied by the cloud, and ρ_0/ρ_h is the ratio of the air density at sea level to the air density at the height h of the center of the cloud.

h feet	0	10,000	20,000	30,000	40,000	50,000	60,000	70,000
ρ_0/ρ_h	1.000	1.35	1.87	2.63	3.95	6.58	10.58	17.11

For the sake of orientation, suppose that after one hour the cloud occupies 10 cubic miles and its mean height is 40,000 feet; then the gamma ray intensity in the center of the cloud would be 720 Roentgens per hour. Fifteen minutes after the explosion, the cloud will probably occupy 7 cubic miles and have a mean height of around 30,000 feet, in which case the gamma ray intensity at the center of the cloud would be 2750 Roentgens per hour. At the edge of the cloud, the gamma ray intensity decreases by a factor of ten dur to the absorption in air for each distance of 500 (ρ_0/ρ_h) yards away from the fringe of the cloud. Thus, using our examples, a pilot willing to accept 36 Roentgens per hour could come a distance of 2000 yards from the cloud at the end of an hour or 2100 yards at the end of 15 minutes. Since the above orders of magnitude are approximately correct, we should be safe in advising the airplane pilots to stay at a distance of 2 miles from the cloud at all times (and never come within a mile). The number of Roentgens which a pilot would get in flying directly through the cloud would not be prohibitive because of the short length of time which he would remain in the cloud. However, the plane would pick up an unpredictable amount of contamination which might be extremely dangerous and therefore no planes should knowingly fly through the cloud during the first day.

[redacted]

[redacted]

A. First Cross-Roads Shot

It is difficult to know exactly what fraction of the fission products will be deposited in the sea water and on the ships. However, in the Trinity shot where the bomb was exploded at a height of 100 feet, approximately 1% of the fission products were deposited within a radius of about 1000 feet; in the Nagasaki shot where the bomb was exploded at a height of 1800 feet, approximately 0.025% of the fission products were deposited within a radius of about 2000 feet. Interpolating between these two sets of experimental points we conclude that in the First Cross Roads Test, 0.2% of the fission products will be deposited within a radius of about 1500 feet.

We are interested in the dosage of gamma rays at different places due to these fission products deposited in the water. Because of the importance of the problem from the standpoint of personnel safety it is advisable to make a careful formulation. Let us suppose that the fission products are distributed in the water with a concentration which varies both with depth and with horizontal position. Let

G = number of MEV gammas emitted by a cubic centimeter of water in one hour corresponding to the concentration of the fission products at the volume element in question.

$\overline{(r/\lambda)}$ = the distance in mean-free paths in a direct line between the volume element and the point in question. Thus in this line if the distance r_1 is in medium 1 and r_2 in medium 2, then $\overline{(r/\lambda)} = \frac{r_1}{\lambda_1} + \frac{r_2}{\lambda_2}$. Here of course the λ's are the mean free paths, ($\lambda = 2\text{x}10^4$ cm for normal air, 22.8 cm for sea water, etc.).

Then:

$$\text{Roentgens per hour at a point} = 1.8\text{x}10^{-10} \int \frac{G \exp(-\overline{r/\lambda})}{4\pi r^2} \, d\,\text{Volume} \qquad (3)$$

[redacted]

[redacted]

The dosage is very sensitive to the exact geometry and the distribution of the fission products.

As a special limiting case let us suppose that the fission products are spread unformly throughout the water, i.e. G is a constant. Then:

Roentgens per hour at a point in the water = $4.8\times10^{-10}G$

If we assume that 0.2% of the fission products are uniformly distributed in the 3×10^{16} cm^3 of water in Bikini lagoon, after a time of t hours, G = 50,000/t MEV gammas per hour. Thus, since the mean free path of the gammas in sea water is 22.8 cms,

Roentgens per hour at a point in the water = $5.5\times10^{-4}/t$

Just above the surface of the water (of the order of three feet), the dosage is about 1.2 times as large and then falls off with increasing height above the water surface. If all of the fission products from the bomb were deposited uniformly in the water of the lagoon, the dosage would be 500 times as great but this would still be phyiologically safe immediately after the explosion.

The fosage in the air above the radioactive water is of interest to the monitors. It is convenient to define the surface activity, S_a, as the number of MEV gamma rays emitted per hour by the fission products in the upper 22.8 cms of the sea water, i.e. $S_a = 22.8\ G_{surface}$. Then in the air at a height of h feet directly over the center of a cylindrical deposit of fission products of radius R feet in the water

$$\text{Roentgens per hour at a height } h = (1/2)S_a\ 4.8\times10^{-10}\left[-Ei(-h/660 + Ei\left(\frac{-h}{660}\sqrt{1+\left(\frac{R}{h}\right)^2}\right)\right]$$

Here $-Ei(-x) = \int_x^{\infty} \frac{e^{-x}}{x}\,dx$ is the well-known integral logarithm tabulated in WPA tables and elsewhore. It is convenient to express

$$\text{Roentgens per hour at height } h = \phi_h S_a\ 4.8\times10^{-10}$$

[redacted]

UNCLASSIFIED

33

[redacted]

Here α_h is the factor which expresses the variation of the dosage with height above the surface of the water. If R = 1500 feet, α_h has the values:

h(feet)	1	3	10	20	30	50	100	200	300	500	1000	1500
α_h	2.95	2.40	1.79	1.458	1.262	1.022	0.711	0.433	0.294	0.154	0.040	0.012

Below the surface of the water α has approximately the value 1.00. If in the first shot, 0.2% of the fission products are deposited in the sea water to a radius of R = 1500 feet, then before the vertical diffusion carries an appreciable fraction of the fission products below 22.8 cms beneath the water surface,

$$4.8 \times 10^{-10} S_a = 110/t$$

W. G. Penney (see B-15 Report X-1) has considered the reduction in the dosage above the surface due to the downward diffusion of the fission products. He assumes that at zero time the fission products are spread on the surface of the sea-water and that they diffuse downwards with an eddy diffusivity, K, (see "The Oceans" by Sverdrup, Johnson, and Fleming). If S_a is the surface activity as a function of time if all of the fission products remained on the surface, the density of the radioactive products at a depth x(cms) at a time t(hours) is given by:

$$G = \frac{S_a}{\sqrt{\pi K t}} e^{-x^2/4Kt} \quad \frac{\text{MEV gammas}}{\text{cm}^3 \text{ hour}}$$

Letting λ = 22.8 cms be the mean free path of the gammas in sea water, due only to the downward diffusion of the fission products, the radioactivity at the surface decreases with time by the factor η:

$$\eta = e^{Kt/\lambda^2} \left[1 - P\left(\frac{\sqrt{Kt}}{\lambda}\right)\right] = \frac{\lambda}{\sqrt{\pi K t}} \left(1 - \frac{\lambda^2}{2Kt} + \frac{3\lambda^4}{4K^2t^2} - \dots\right)$$

Here $P(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-z^2} dz$ is the usual probability integral.

Both Comdr. Revelle and Penney believe that K = 1 cm^2/sec = 3600 cm^2/hour is conservative.

[redacted]

[redacted]

In this case:

t(minutes)	0	1	3	5	10	20	30	60	120	240
η	1.000	.7077	.5729	.5035	.4080	.3186	.2708	.1993	.1461	.1053

In the limit that the fission products are uniformly distributed to the full depth of the lagoon, η = .01. Thus, four hours after the shot, the radioactivity above the surface will be reduced by a factor of ten just due to vertical diffusion. Altogether, the dosage at a height of 3 feet above the water after the first shot will be: 264/t(hours) Roentgens/hour. Or 52.6 Roentgens/hour at the end of the first hour; 19.3 Roentgen/hour at the end of the second hour; 6.9 Roentgen/hour at tne end of the fourth hour.

Altogether, the gamma ray dosage at a time of 5(hours) after the first shot at a height of h(feet) above the center of the radioactive water is given by:

Roentgens per hour = $110\lambda\eta/t$

Or as shown on the following chart:

Roentgens per hour

t(minutes) \ h(feet)	3	10	30	50	100	200	300	500	1000	1500
1	11200	8360	5900	4770	3320	2020	1370	720	187	56
3	3024	2255	1590	1288	896	546	370	194	50	15
5	1596	1190	839	680	473	288	196	102	27	8
10	646	482	339	275	191	116	79	41	10.8	3.2
20	252	188	133	107	75	45	31	16	4.2	1.3
30	143	107	75	61	42	26	18	9.2	2.4	.72
60	53	39	28	22	16	9.5	6.4	3.4	.88	.26
120	19	14	10	8.2	5.7	3.5	2.4	1.2	.32	.10
240	7.0	5.2	3.7	3.0	2.1	1.3	.85	.45	.12	.035

[redacted]

[redacted]

The above estimates are conservative. For example it is expected that the radioactivity will further be reduced to a slight extent by the horizontal diffusion of the fission products. Thus Sverdrup estimates that at the end of 4 hours the radioactivity at the center is decreased to 95% due to horizontal diffusion; after 12 hours it is decreased to 90%; after one day, to 52%; after 2 days to 18%; after 4 days to 19.5%.

In considering the radioactivity of the sea-water, it should be remembered that there is an average wind from the east of 15 to 20 mph on the surface of the water which blows the surface water 0.5 mph towards the west. Thus in two hours we can expect that the center of the radioactive sea-water will have moved a distance of one mile from the target point. The motion of the water below the surface is now being determined by the oceanographers on the Bowditch, but it is certain that at some strata near the bottom, the water must move towards the east and help to diffuse the fission products still further by transfer between counter-currents.

The induced radioactivity of the sea water is negligible. If the explosion is rated at 20,000 tons of TNT, approximately $4x10^{24}$ neutrons are formed. The majority of these are prompt neutrons which are slowed down to epi-thermals before emerging into the air. The range of the epi-thermals in air is small and they are absorbed by the nitrogen (to form C^{14}). Only 0.35% of the neutrons are delayed. These have mean-free paths of the order of 300 meters in air and they succeed in reaching the sea-water, provided they start out in the right direction. From the medical evidence at Nagasaki and Hiroshima it appears that a small fraction of the prompt neutrons also will get to the sea-water. Theoretical work on the neutron spectrum as a function of distance is now under way and will be reported later. However, it would appear

[redacted]

34

[redacted]

that a liberal estimate of the neutron flux is obtained by supposing that 0.5% of the neutrons formed are uniformly spread over the sea-water to a radius of 1500 feet. Thus we suppose that there are $3x10^{12}$ neutrons per cm^2 hitting the surface of the sea within this circle.

The three important neutron absorbers in the sea water are the hydrogen of the water and the sodium and chlorine of the salt. The hydrogen has a cross-section of $.31x10^{-24}cm^2$ to form deuterons with the emission of a prompt 2.14 MEV gamma. Thereafter the deuterons remain radioactively inert. The sodium 23 has a cross-section of $.4x10^{-24}cm^2$ for absorbing neutrons to form sodium 24 with a half-life of 14.8 hours emitting gamma rays of approximately 2 MEV's. The chlorine 37 (which comprises 25% of the chlorine) has a cross-section $.61x10^{-24}cm^2$ to form chlorine 38 which has a half-life of 37 minutes emitting gamma rays of approximately 2 MEV. If we assume that the sea-water is made up of 27 grams of NaCl for each 1000 grams of H_2O, it follows that 98.6% of the neutrons are absorbed in the hydrogen; 0.83% in the chlorine; and 0.55% in the sodium. If we let t be the time in hours after the explosion it follows:

$$\frac{\text{Number MEV gammas from Cl}}{\text{cm}^2 \text{ of surface hour}} \equiv 1.02x10^{+10}x10^{-t/1.42}$$

$$\frac{\text{Number MEV gammas from Na}}{\text{cm}^2 \text{ of surface hour}} = 2.28x10^9x10^{-t/34.1}$$

In this region, the activity from 0.2% of fission products deposited to the same radius is $5.28x10^{12}/t$ MEV gammas/cm^2-hour. Thus the induced activity in the sodium and the chlorine is less than 1% of the activity of the deposited fission products. The exact amount of induced activity is sensitive to the concentration of rare earths, plankton, etc., but the above calculation suffices to show its order of magnitude.

[redacted]

[redacted]

It is difficult to estimate the induced activity on the ships. Theoretical work is being carried out on this problem at the present time and will be reported later. However, some general considerations may be given here. The ships are composed mostly of steel. The iron in the steel absorbs most of the neutrons to give off a prompt gamma. Most of the later activity of the steel is due to the manganese. If y is the percentage of manganese in the steel (a high tensile strength steel has around 1.25% manganese, milder steels have a smaller percentage),

Number MEV gammas per hour per neutron absorbed in steel = $.058\ y\ 10^{-t/6}$

The induced activity in copper is slightly higher and lasts longer.

Number MEV gammas per hour per neutron absorbed in copper = $.098 \times 10^{-t/29.4}$

[redacted]

B. Second Cross-Roads Shot

In the second Cross-Roads shot where the bomb is either exploded just below the water surface or at the bottom of the lagoon, we expect that most of the radioactivity will be uniformly distributed in a cylinder 1000 feet in radius and extending to the full depth of 180 feet. In this cylinder there will be approximately 5% of all of the fission products and the products formed by the absorption of approximately 50% of all of the neutrons formed. This cylinder contains 1.6×10^{13} cubic centimeters.

Since the total amount of fission products yields $7.6\times10^{23}/t(\text{hours})$ MeV gammas per hour, it follows that due to the fission products, we have

$G_{\text{fission}} = 2.4\times10^{9}/t(\text{hours})$ MEV gammas per cm^3 per hour

The total number of neutrons which are formed is of the order of 3.8×10^{24}. If 50% of these are absorbed in 1.6×10^{13} cm^3, we have 1.2×10^{11} neutrons absorbed per cm^3 of water. Using the same type of analysis for the induced activity in the sea-water as in the first shot, we find:

G_{Cl} = Number of MEV gammas from Cl per $\text{cm}^3 = 4.1 \times 10^{8} \times 10^{-t/1.42}$

G_{Na} = Number of MEV gammas from Na per $\text{cm}^3 = 9.1 \times 10^{7} \times 10^{-t/34.1}$

To show the relative importance of these three terms we have prepared the following chart:

t(hours)	1	2	4	12	24	48
G_{fission}	2.4×10^{9}	1.2×10^{9}	6×10^{8}	2×10^{8}	10^{8}	5×10^{7}
G_{Cl}	8.1×10^{7}	1.6×10^{7}	6×10^{5}	1.5×10^{0}		
G_{NA}	8.5×10^{7}	7.9×10^{7}	6.9×10^{7}	4×10^{7}	1.8×10^{7}	3.6×10^{6}

Thus the radiactivity due to the deposited fission products is always about 10 times as large as the induced activity of the sea-water.

[redacted]

39

[redacted]

Thus the dosage over the sea-water is given by

Roentgens per hour above the water = $\alpha 29/t$(hours)

Or at a height of 3 feet above the surface since $\alpha = 2.40$

Roentgens per hour 3 feet above surface = $70/t$(hours)

This is shown in the following chart:

t(minutes)	1	3	5	10	30	60	120	240
Roentgens per hour 3 feet above water	4200	1400	840	420	140	70	35	18

Thus the radioactivity above the surface of the water is roughly comparable to the first shot. In the first thirty minutes, the second shot gives less activity and thereafter slightly more.

[redacted]

40

[redacted]

B-15 REPORT II-1

AIR BLAST PRESSURE AS A FUNCTION OF DISTANCE ALONG THE SURFACE OF THE WATER

The attached curve gives the shock overpressure as a function of distance along the water surface for a bomb where the energy equivalent of 20,000 tons of TNT of nuclear energy is released and the bomb is dropped as in Test A from 600 feet height. The calculations were made by K. Fuchs using I.B.M. computing machines on the basis of starting conditions and equation of state of air furnished him by Hirschfelder and Magee. The energy in the blast is considerably smaller (i.e. around 50%) of the energy which would be expected from a normal bomb.

At large distances the overpressure is given by the equation:

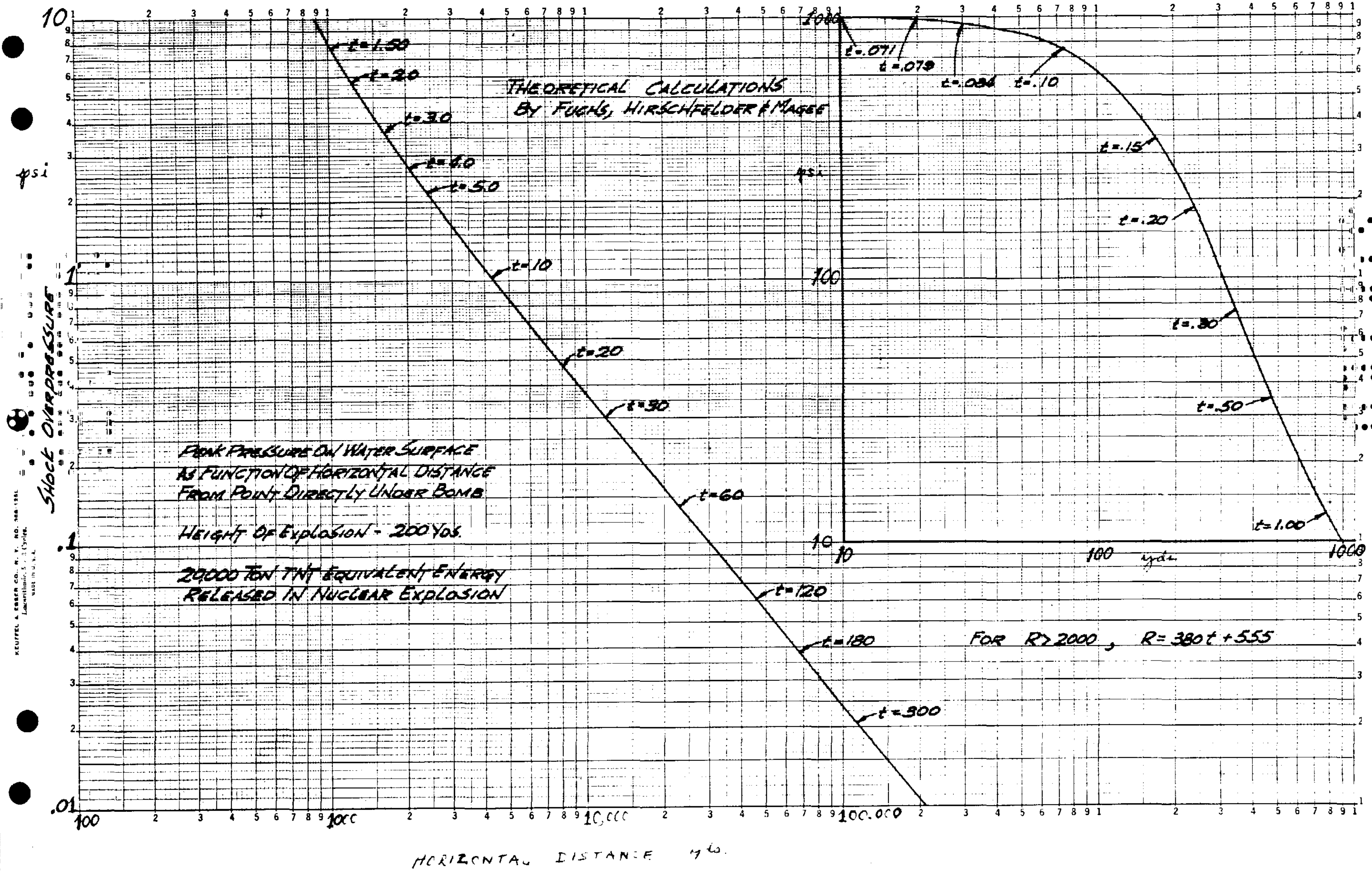
$$p(\text{psi}) = \frac{27.40}{\left(\frac{R}{W^{1/3}}\right)\sqrt{\log_{10}\left(\frac{R}{W^{1/3}}\right) - .662}}$$

Here R is the distance from the explosion in feet.

W is twice the effective charge weight in pounds. The factor of two arises because of the reflection of the shock on the water surface.

For distances greater than 2000 yards the time of arrival of the shock, t (sec) is given by R (yds) = 380 t + 555.

[redacted]



THEORETICAL CALCULATIONS
BY FUCHS, HIRSCHFELDER & MAGEE

PEAK PRESSURE ON WATER SURFACE
AS FUNCTION OF HORIZONTAL DISTANCE
FROM POINT DIRECTLY UNDER BOMB

HEIGHT OF EXPLOSION - 200 YDS.

20000 TON TNT EQUIVALENT ENERGY
RELEASED IN NUCLEAR EXPLOSION

FOR R > 2000, R = 380 t + 555

42

[redacted]

B-15 REPORT II-2

PENNEY FLAG-POLE PRESSURE GAUGE[1]

Penney believes that an excellent pressure gauge is obtained by exposing a series of rods of pipes of different lengths to a blast. All of the rods down to a critical length will be bent. This critical length is a good indication of the blast pressure. Since the dimensions of the pipes are small compared to the length of the blast wave, the applied pressure may be considered to be hydrostatic.

If the pipe has the length L and a radius R, the exposed area of the pipe is 2LR. The drag pressure on the pipe is given by $S = 1/2\ C_D\ \rho_s\ u_s^2$ where ρ_s is the shock density of the air, u_s is the material velocity of the air right behind the shock front, and C_D is the usual drag coefficient for a smooth cylinder. The value of C_D is almost 1/2 but it has a small variation with Reynold's number. The value of $\rho_s u_s^2$ can be tabulated as a function of the shock pressure. (See for example OSRD 3550). Actually, $\rho_s u_s^2$ is a very sensitive function of the shock pressure and therefore the gauge is sensitive. The thrust on the pipe is 2LRS and the bending moment is L^2RS. Theoretically the critical bending moment is

$$(4/3)Y\ (a^3-b^3)$$

where Y is the tensile strength of the pipe and a and b are its outer and inner radii respectively. However, it is best to determine the critical bending moment experimentally from a testing machine.

It is also possible to tell the shock pressure from the angle at which a given pipe is bent but this requires a rather elaborate analysis since the thrust and the bending moments vary with the angle through which the pipe has been bent.

---

[1] Private communication from W. G. Penney.

[redacted]

[redacted]

B-15 REPORT II-3

PENNEY TIN CAN PRESSURE GAUGE[1]

Penney uses as a pressure gauge ordinary five gallon gasoline cans with a small opening at one end. The can is collapsed until the volume is reduced so that the inside pressure is equal to the outside pressure (except for a small term due to the strength of the can). The dimensions of the can are small compared to the length of the shock wave so that the pressure on the outside may be considered to be hydrostatic. The hole in the can is so small that in the time required to collapse the can, very little air can pass through it; but the hole is large enough that the air can flow out during the suction phase so that the original dimensions of the can are not restored. Penney is going to improve these cans by placing a disc over the hole in such a way that in the pressure phase no air can come in but the air can rush out freely in the suction phase.

Under these conditions it is clear that the shock overpressure, P (atms.), is given by the equation:

$$P(\text{atms.}) = \left(\frac{\text{initial volume can}}{\text{final volume can}}\right)^{1.4} - 1 + P_{\text{structural}}$$

Here $P_{\text{structural}}$ is due to the structural strength of the can and is almost constant with pressure. It is determined by calibrating the cans.

Penney recommends measuring the final volume of the can by filling the can full of water and weighing with a spring balance.

[redacted]

---

[1] Private communication from [illegible] Penney.

#4 [redacted]

B-15 REPORT II-4

ANALYSIS OF EFFECIENCY OF GADGET EXPLOSION FROM SHOCK-RADIUS TIME CURVES OBTAINED BY FASTAX CAMERA

It seems altogether possible that a satisfactory estimate of the efficiency of the nuclear explosion in the Cross-Roads Test A may be obtained from curves of the shock radius as a function of time in the early stages (shock radius 40 to 125 meters; time up to 25 milliseconds). These curves may be obtained from the Fastax camera records.

Bethe attempted to make a similar analysis of the results of the Trinity shot with very poor results. The reason for this (as concluded by Bethe, Fuchs, et al) was that in the Trinity shot the reflected shock wave passed up through the incident shock soon after the ground was hit when the radius of the shock was only 30 meters. After this time it is difficult to interpret the results, because of the unknown effect of the reflected shock. And before this time it is not justifiable to assume that the similarity solution is valid because of the large amount of material in the gadget itself and also because of the effect of the radiation kinematics. However, such objections would not hold for the Cross-Roads Test A where the height of the explosion will be of the order of 150 meters. In this case the radius-time curve should be interpretable of the basis of a similarity solution from the time the radius is 40 meters until it is 125 meters.

The similarity solution can be obtained from either Taylor's theory (BM-35 or RC-210; or LA-213) or from Bethe's Small Gamma Minus One Theory (Article to be published in the Los Alamos Encyclopedia). The former starts out with an explosion from a point source and has the disadvantage

[redacted]

[redacted]

that the temperature distribution inside is unreasonable. Bethe's theory starts with an isothermal sphere and lets the explosion develop from it. The two theories agree (except for unimportantly small numerical discrepancies) in the intermediate phase of the explosion when the shock pressure is greater than 25 atmospheres and after the shock has expanded to the point where the original amount of material in the gadget is negligible compared to the weight of air which has been shocked.

Using the constants which we obtained from the Small Gamma Minus One theory together with gamma equal to 1.25, we have the following relations between shock pressure, p_s(bars); the shock radius, R(yards); and the time, t(sec) where E is the energy of the explosion expressed in equivalent tons of TNT:

$$R = 81.27\ E^{1/5}\ t^{2/5}$$

$$p_s R^3 = 5436\ E$$

If we take the Taylor solutions as given in LA-213 and interpolate for gamma equal to 1.25, we get: $R = 82.49\ E^{1/5} t^{2/5}$ and $p_s R^3 = 5678\ E$

The numerical difference between these two solutions is negligible compared to other errors which arise.

From a set of the Fastax pictures it will be possible to plot the radius, R, versus time. However, it will not be possible to know the zero of time. Let T_1 and T_2 be times measured with respect to an arbitrary zero and R_1 and R_2 be the radii measured at these time. Then from eq. (1) the energy in tons of TNT is given by

$$E = \left(\frac{R_1}{81.27}\right)^5 \left[\frac{1 - \left(\frac{R_2}{R_1}\right)^{5/2}}{T_1 - T_2}\right]^2$$

[redacted]

UNCLAS
SIFIED 46

[redacted]

B-15 REPORT II-5

The airborne pressure gauges should give accurate pressure-time curves which can be used to interpret the energy released by the nuclear explosion. There are four features of the records which are significant: (1) peak overpressure, p (psi); (2) duration of positive pulse, τ (sec); (3) positive impulse, I (psi-sec); (4) energy in the positive pulse, E_{blast} (tons TNT). Perhaps the energy in the positive pulse is the best criterion for the gadget efficiency since it is not sensitive to the shape of the shock pulse (although of course it is sensitive to instrumental errors which do not average out on the integration).

In the Nagasaki and Hiroshima explosions the bombs exploded at such a high elevation that the shock hit the ground. On this account the reflected shock traveled slower than the intial shock and the two shocks arrived at the airborne gauges separately with a time interval of about 1.5 seconds between. This made it necessary to base the interpretations of energy released just on the peak pressure of the initial shock. In the Cross-Roads Test A, the suction phase will not be formed by the time that the shock hits the ground and no such complications are anticipated.

The analysis will proceed in the following manner:

(1) PEAK OVERPRESSURE.

From the calculations of Fuchs, Hirschfelder, and Magee (see B-15 Report II-1) it appears that the shock overpressure on the ground at a long distance from the explosion is given by the equation:

$$p(\text{psi}) = \frac{27.40}{\left(\frac{R}{W^{1/3}}\right)\sqrt{\log_{10}\left(\frac{R}{W^{1/3}}\right) - .662}}$$

[redacted]

[redacted]

Here R is the total distance from the explosion in feet and W is twice the equivalent weight of TNT in pounds. The factor of two arises because of the shock on the water surface.

The shock pressure at a height of h(ft) is smaller by a factor, f, than would be expected of the same shock at the same distance from the explosion but with the gauge placed at sea level. According to Bethe the factor f is given by the relation:

$$f = (P_h/P_g)^{1/2.8}\,(T_h/T_g)^{0.25}$$

Here P_g and T_g are the normal atmospheric pressure and temperature at ground or sea level and P_h and T_h are the barometric pressure and temperature of the air at the altitude h. Using the United States Standard Atmosphere (AM-345) we find:

h feet	P mm Hg	T deg. Kelvin	f 1.0000
0	760	288.1	1.0000
15,000	428.8	258.4	.7931
20,000	349.1	248.5	.7299
25,000	281.9	238.6	.6695
30,000	225.6	228.7	.6117
35,000	178.7	218.9	.5567

From the meteorological data taken just before and just after the shot we can get a slightly better value of f.

Thus at the height h we expect the shock overpressure to have the value:

$$p_s(\text{psi}) = \frac{27.40\,f}{\left(\frac{R}{W^{1/3}}\right)\sqrt{\log_{10}\left(\frac{R}{W^{1/3}}\right) - .662}}$$

[redacted]

[redacted]

If we know the height of the gauge, we know f. The distance of the gauge from the explosion gives R and the shock overpressure is given by the gauge signal. The value of W is determined from the above equation by substituting a series of possible values of W into the equation and computing the corresponding value for p_s(psi). The correct value of W gives a value of p_s(psi) which agrees with the gauge signal. The energy of the explosion in equivalent tons of TNT is then

$$E = W/1000$$

The time t(sec) required for the shock to reach the gauge after the explosion may be used as a measure of R since

$$R = \frac{1140\ t(\mathrm{sec}) + 1665}{\sqrt{1/2 + 1/2(T_h/T_g)}}$$

The disadvantage of using the shock overpressure to determine the efficiency is that essentially p_s varies only as $E^{1/3}$.

(2) DURATION OF THE POSITIVE PULSE

The duration of the positive pulse is a function only distance from the explosion and not a function of altitude. From the I.B.M. calculations we obtain at very large distances the limiting law:

$$(\mathrm{seconds}) = .0023\ W^{1/3} \log_{10}(R/W^{1/3}) - .662$$

Here R is the distance to the explosion in feet and W is twice the equivalent weight of TNT in pounds. The duration of the positive pulse varies as the one-third power of the charge weight and therefore is not a very good criterion of the energy released.

(3) POSITIVE IMPULSE

The positive impulse, I, varies in the same manner as the shock overpressure with altitude. It is defined by the relation $I = p(\mathrm{psi})dt$.

[redacted]

[redacted]

From the I.B.M. calculations we obtain at very large distances the limiting law:

$$I(\text{psi-seconds}) = .035fW^{2/3}/R$$

Here again f is the factor reducing the shock overpressure because of altitude of the gauges; W is twice the equivalent weight of TNT in pounds; and R is the distance to the explosion in feet. The positive impulse is a more sensitive criterion of energy released than either the shock overpressure or the duration of the positive pulse.

(4) THE ENERGY IN THE POSITIVE PULSE OF THE BLAST

The energy in the positive pulse of the blast, E_{bl}(tons TNT), may be written

$$E_{bl}(\text{tons TNT}) = \frac{1.319\ (R/300(^2\ p^2(\text{psi})dt(\text{sec})}{f^2}$$

Here R is again the distance from the explosion in feet.

From the I.B.M. calculations we obtain the limiting form

$$E_{bl}(\text{tons TNT}) = \frac{5 \times 10^{-5}\ W}{\sqrt{\log_{10}(R/W^{1/3}) - .662}}$$

This is a sensitive criterion of energy released because E_{bl} is proportional to W.

(5) INTERPRETATION OF NORMAL TNT EXPLOSIONS

If in making our interpretations we had used the equations which apply to normal type of explosions (LA-316), the constants which appear in our equations would have been quite different. The shock overpressure would be given by the relation:

$$p(\text{psi}) = \frac{35\ f}{(\frac{R}{W^{1/3}})\sqrt{\log_{10}\ (R/W^{1/3}) - .928}}$$

[redacted]

[redacted]

The positive impulse would have been

$$I(\text{psi-sec}) = \frac{0545\ f\ W^{2/3}}{R}$$

And the blast energy would have been

$$E_{bl} = \frac{8.4 \times 10^{-5}\ W}{\sqrt{\log_{10}(R/W^{1/3}) - .928}}$$

Thus at very large distances it would appear from the shock overpressure that the energy released is 50% of the energy appearing in the blast; from the positive impulse this factor would be 64%; and from the blast energy about 60%.

[redacted]

57

[redacted]

B-15 REPORT II-6

PRESSURE TIME CURVES AT VARIOUS DISTANCES

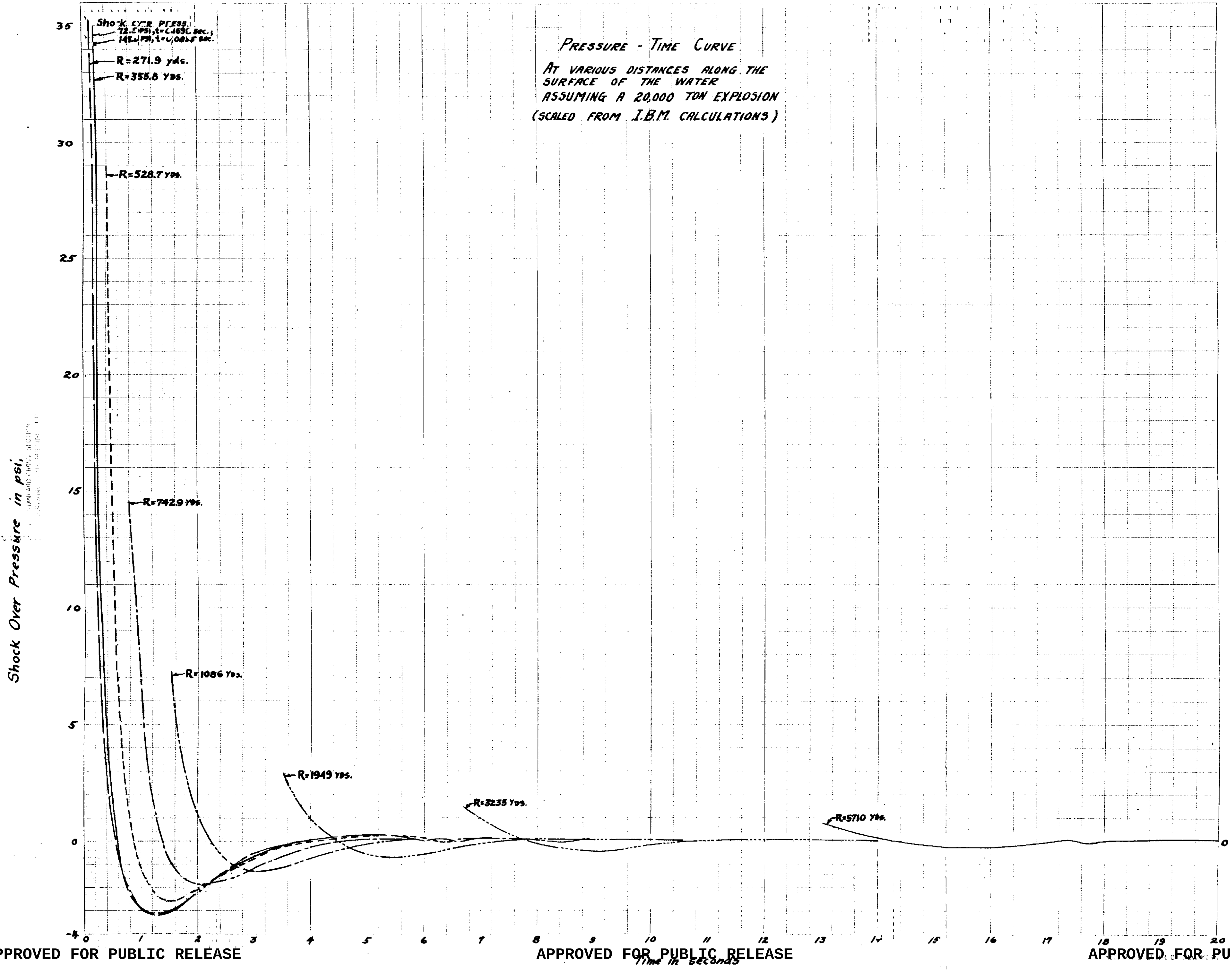
On the attached graph will be seen the pressure time curves obtained in the I.B.M. calculations, scaling the explosion to 40,000 tons of T.N.T. in air or 20,000 tons of T.N.T. assuming the usual doubling on reflection. The results may be summarized by the following table.

For 20,000 tons
(With Doubling for Ground Reflection)

R(yds)	p_{shock} (atm) overpress.	I_+(psi-sec)	τ_+(sec)	$E_{in\ blast}$ (tons TNT)
272	10	8.90	.466	7500
356	5	5.01	.392	3100
529	2	3.54	.442	2100
743	1	2.67	.576	1560
1086	.5	1.92	.723	1260
1950	.2	1.09	.938	950
3235	.1	.677	1.132	830
5710	.05	.379	1.294	730

Here R is the distance from the explosion in yards, the shock overpressure is in atmospheres, the I_+ (per sec) is the pressure time impulse, τ_+ (sec) is the time duration of the positive blast, and $E_{in\ blast}$ is the energy which remains in the blast expressed in tons of TNT. Thus, when the energy in the blast is 2100 tons, since the original explosion was 20,000 tons, only 10 1/2 per cent of the energy of the explosion still remains in the form of a blast.

[redacted]



PRESSURE - TIME CURVE

AT VARIOUS DISTANCES ALONG THE SURFACE OF THE WATER ASSUMING A 20,000 TON EXPLOSION (SCALED FROM I.B.M. CALCULATIONS)

53

[redacted]

D-15 REPORT VI-1

RADIATION INTENSITIES AND HEATING EFFECTS

1. Intensities of Illumination

The accompanying figure gives a theoretical curve which is useful for calculating illuminations at any distance and time. The left scale gives (yards)^{2}x suns and the right scale gives suns at 10,000 yards. The "sun" unit [⊙] is taken to be the solar constant, 1.94 calories/cm^2 minute. At a distance of 10,000 yards the radiation is attenuated by approximately the same amount of air as the noon-day sun's rays.

In calculating the $D^2⊙$ values it was assumed that only light of longer wave length than 3150 Å is transmitted. This was observed to be true at the "Trinity" test. The distribution of wave lengths longer than 3150 Å should be very nearly that of black body radiation of some characteristic temperature. Values of the temperature are given along the curve.

The radiation intensities in the initial phase, almost to the minimum in the curve, are completely determined by the equation of state of air and the hydrodynamical calculation (on I.B.M. machines) of the air blast. The values in the vicinity of the minimum and beyond are somewhat less certain since they are determined by details of the behavior of the NO_2 concentration, and this has not been worked out very carefully. Theoretically the <u>total</u> radiation given off during this period is more certain than the absolute intensity or the duration individually. From Trinity measurements it is known that the duration is about ten seconds. Since NO_2 radiates strongly in the visible and very little in the near infra-red, it is predicted that the intensity should fall suddenly to near zero when the gases cool down to about 2000°K.

[redacted]

[redacted]

The total amount of radiation given off (by integrating the curve) is found to be the equivalent of 4400 tons of TNT, or 22% of the yield. The Trinity value was found to be about 18%.

2. Heating effect

For objects which do not come into direct contact with the ball of fire, heating and charring effects are due principally to the initial burst of radiation of high intensity. During this time the radiation is richer in short wave lengths which are more strongly absorbed in common objects (wood, cardboard, metals, cloth, etc) than the low temperature radiation of the later stages. The temperature of the shock is above 10,000°K until the shock radius is 60 yards, at 3.7 milliseconds.

A simple way to calculate maximum surface temperatures is obtained by approximating the first radiation burst as a square pulse; let us say that the value of $D^2\Theta$ is constant at 4.5×10^9 for 0.020 seconds. The maximum surface temperature reached for an object a distance D yards away is given by

$$\Delta T_s = \frac{1.89\times10^9}{D^2}\,\frac{\alpha}{\sqrt{K\rho C}}\ {}^\circ F \qquad 1.$$

or

$$\Delta T_s = \frac{1.05\times10^9}{D^2}\,\frac{\alpha}{\sqrt{K\rho C}}\ {}^\circ C \qquad 2.$$

where α is the fraction of the light absorbed by the surface, K is the thermal conductivity in $\frac{\text{Btu}}{\text{Ft-hr-}^\circ\text{F}}$, ρ is density in $\frac{\text{lb}}{\text{ft}^3}$, C is specific heat in $\frac{\text{Btu}}{\text{lb-}^\circ\text{F}}$.

Substituting values for pine wood (with $\alpha = 1$) gives:

$$\Delta T_s = \frac{7.45\times10^8}{D^2}\ {}^\circ C \qquad 3.$$

The charring of a substance like wood is most likely a simple decomposition

[redacted]

[redacted]

reaction, and it is almost true that a temperature criterion can be given for the effect; i.e., charring occurs noticeably or not depending upon the maximum temperature attained. If we assume for the moment that 400°C is necessary, the maximum value of D for which this temperature rise is possible is found to be 1360 yards.

Surface temperatures of all poor heat conductors will tend to be high for such moderate distances. Metals, on the other hand, cool their surfaces by conducting the heat away. Copper, for example, has:

$$\Delta T_s = \frac{3.14 \times 10^7}{D^2} \alpha \qquad 4.$$

The value of α is about 0.75. Thus temperature increments for copper is approximately 1/30 that of pine for the same distance.

Copper melts at 1083°C. Calculating the radius at which melting can occur gives 150 yards which is well within the ball of fire. Thus one does not expect copper surfaces to be melted by radiation. Lead, with a melting point of 327°C could be melted only to a distance of about 275 yards, and would at this distance be in the ball of fire.

In the table values of $\sqrt{K\rho C}$ and some values of α are given. The ratio $\frac{\alpha}{\sqrt{K\rho C}}$ gives a comparative measure of the temperature rise of various materials at a given distance.

[redacted]

[redacted]

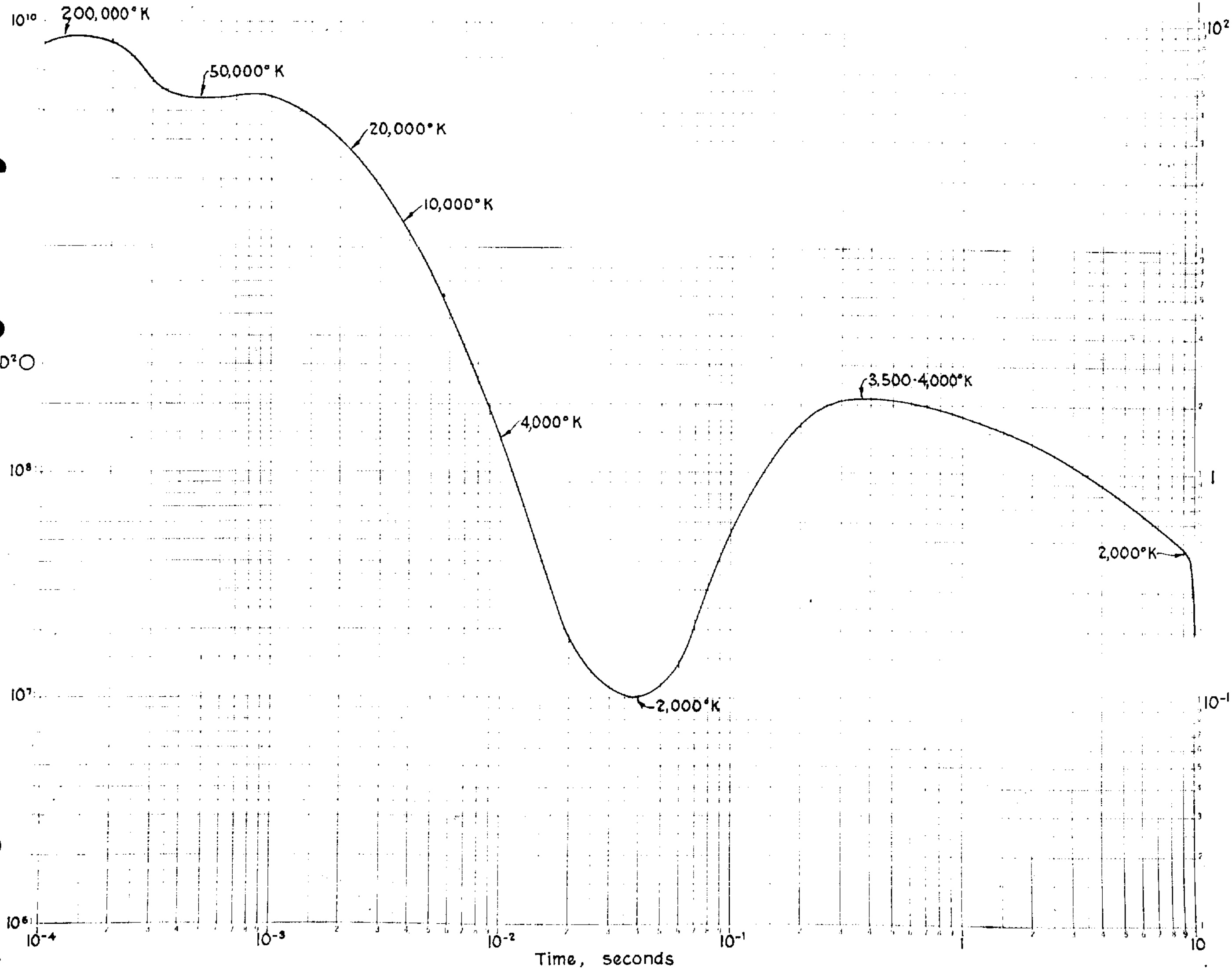
Substance	$\sqrt{K\rho C}$	$\alpha(3500)R)$	Relative ΔT_s
a. Metals:			
Al	67.4	(.5)	0.01
Cu	33.5	0.75	0.031
Pb	21.7	(.5)	0.032
Fe(steel)	42.0	0.55	0.018
b. Structural materials			
Asphalt	5.8	(1)	0.24
Oak	1.9	(1)	0.74
Pine	1.4	(1)	1.0
Balsa Wood	0.4	(1)	3.5
Plaster Board	1.9	(.5)	0.37
c. Various materials			
Cotton	0.2	(.5)	3.5
Cork	0.3	(1)	4.6
Rubber			
hard	5.0	(1)	0.28
soft	1.6	(1)	0.87

[redacted]

FIG. 1

ILLUMINATION

Left scale is (yards)² x "suns"
The "sun" is given by the solar constant 1.94 cal./cm² minute.
The right scale is "suns" at 10,000 yards



[redacted]

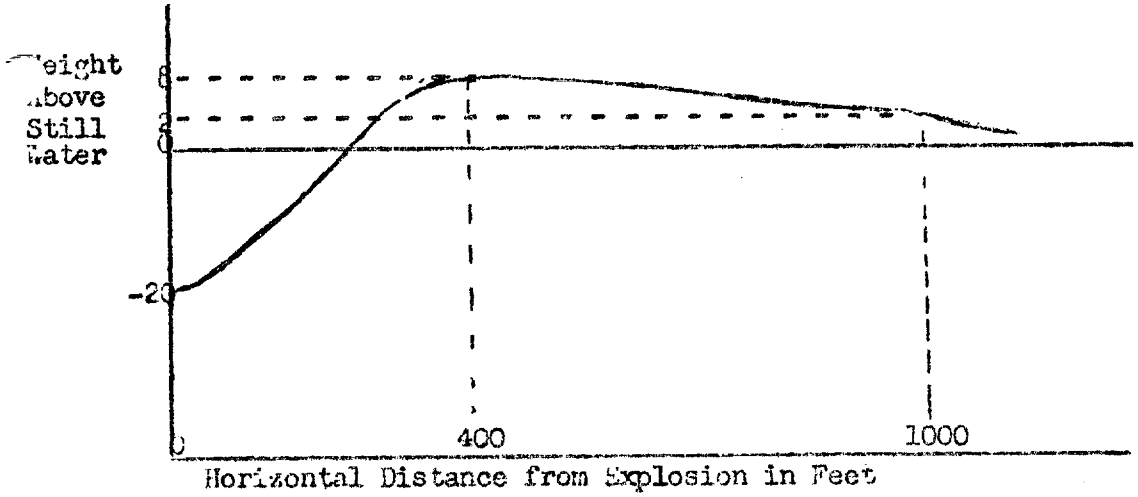
WAVE MOTION

(Based on Two Preliminary Reports by Dean M. P. O'Brien; a Conference with and a Memorandum by W. G. Penney; a Conference and Report by Comdr. Roger Revelle).

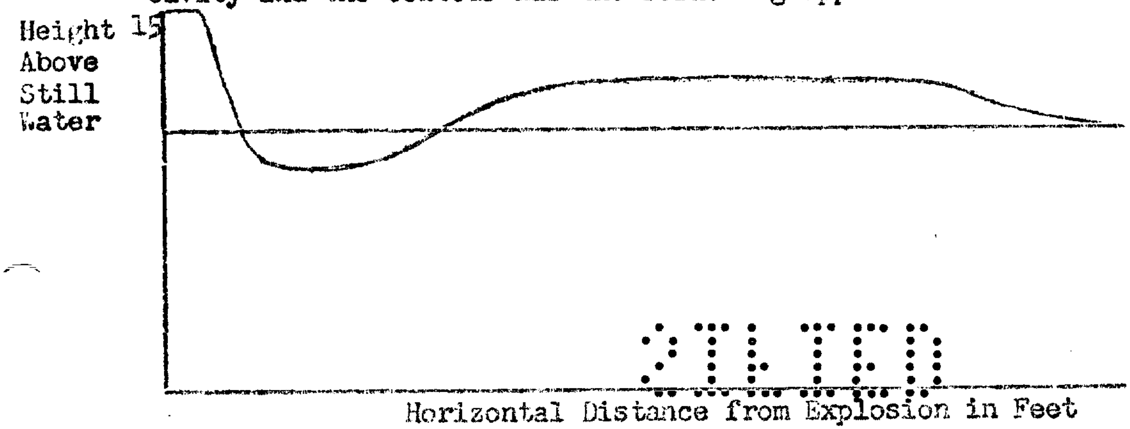
There has been a great deal of speculation on the height of the waves which may be produced by the Cross-Roads explosions. The following predictions are based on the scaling of small explosions.

I. Cross-Roads Air Burst Shot.

Penney has made the only predictions on the wave system resulting from the first Cross-Roads explosion. Assuming that the shot is burst 600 feet above the water surface and releases the energy equivalent of 20,000 tons of TNT, Penney predicts that at the end of the first stage (6 or 7 seconds after the explosion) the water surface will have the following contour:



After roughly 20 seconds, the water has rushed back to fill the central cavity and the contour has the following appearance:



[redacted]

[redacted]

Thereafter the central hump oscillates up and down with a period of the order of ten seconds and with each oscillation it sends out one wave. It is not expected that the wave system from the first shot will be spectacular or do any damage. However, there will be a large amount of water thrown up in the form of spray as the following memorandum from W. G. Penney shows:

"As soon as the Mach Y from the main explosion develops, a vertical blast wave will run across the water. The air motion following the shock will develop instabilities in the water surface, and considerable spray will be thrown off. The air-water mixture is a turbulent region, and the angle of mixing, according to model measurements in a blast tube, is about 15°. If X is the total outward motion of the air at any radius, then the height H which the spray reaches is X/4. At the 10 psi level, the positive blast will last about 0.6 seconds, and X is about 60 feet. Hence the spray will be thrown about 15 feet high at the 10 psi level (for a 20,000 ton blast equivalent, the radius for 10 psi is about 850 yds.). At higher values of peak pressure, the spray will be thrown higher, and as the center of explosion is approached, the spray height increases inversely as the distance. At 500 yards, the spray should reach 25 ft. Closer in than this, the position is uncertain becasue of the complicated shock wave configurations, but it seems unlikely that the blast wave will cause spray to rise above 50 feet. However, small amounts of spray near to the center may be caught in the uprising convection current associated with the ball of fire, and carried to considerable heights."

[redacted]

[redacted]

Much of this spray will be swept into the cloud, become contaminated with fission products, and rain down on the ships downwind. This will leave a radioactive trail of some three or four miles long. An attempt will be made to make a semi-quantitative estimate of the amount of fission products deposited in this manner.

II. Cross-Roads Surface or Sub-Surface Shot.

Dean O'Brien has made a careful survey of all of the experimental and theoretical information which bears on the wave system formed in the second Cross-Roads shot. He does not really have enough information to distinguish between the results of a surface shot and a shot at the bottom of the 180 foot deep lagoon. He concludes that if the explosion releases the energy equivalent of 20,000 tons of TNT:

Horizontal Distance in Feet	2000	50000	10000	15000
Maximum Wave Height from Crest to Trough in Feet	30	12	6	4

The wave length will be 720 feet and the wave-period 14 seconds. The above estimates are liberal and the chances are good that the maximum wave heights will be two-thirds of the listed values. The estimates are based on scaling from:

a) A large number of explosions varying between 0.06 and 600 pounds fired on the surface of a pond.

b) British firing of 8000 lbs TNT at a depth of 5 feet in a pond 9 feet deep.

c) Navy Bu Ord firing at Solomon's Island of 25 tons TNT at the bottom of the bay where the water was 40 feet deep.

d) Port Chicago explosion where 1500 tons of TNT fired in 30 feet of water produced a maximum wave height from crest to trough of 10 feet at Roe Island a distance of 2000 feet.

[redacted]

57d

[redacted]

e) The New Zealand "Seal" firings.

f) The MacMillan-Shapiro firings of small charges and production of artificial wave systems by raising a plunger.

g) Von Neumann's extreme assumptions that 50% of the energy of the explosion goes into water and 30% of this goes into making a cavity. Then this cavity has a radius of 1000 feet which is made completely dry. From the MacMillan-Shapiro results with this size cavity one concludes that the waves should be only a few percent larger than our tabulated values.

There is no serious disagreement in the wave heights expected on the basis of any of the above experiments.

Chronologically the sequence of events is as follows. First, a cylindrical crater will be formed with a radius of from 800 to 1000 feet and extending to the full depth of the lagoon. It will take from 6 to 7 seconds for this to reach its maximum size. The water removed from the crater will be raised above the level of still water and go out ahead of the disturbance; part of the water will be shot out in a spray at an angle of about 60° with the water surface. The water will then return towards the center with a velocity of around 1[illegible]0 feet/second to fill the cavity, form a central mound, and send up a tremendous plume. The central mound will not be fully developed until 20 seconds after the explosion. There have been estimates of the height to which the plume rises which vary from 1500 to 10000 feet - probably 3000 feet would be a conservative estimate. The central mound oscillates and each time it sends off a new wave. The first wave formed on the first downward motion of this mound sends off the highest wave which moves at a velocity of around 75 ft/sec and reaches 1000 feet about 35 seconds after the explosion. When this wave is closer than 1000 feet it is not clearly distinguishable because of the plume etc.

[redacted]

There will be the same type of spray system which Penney discussed in connection with the first shot but it will not be as spectacular as the towering plume. The water from the plume will wash down fission products and leave a radioactive trail of a few miles downwind. The water from the plume will not have a profound effect on the normal cloud formation because the plume does not start upwards for 20 seconds at which time the top of the cloud is about one mile high. The cloud may be sufficiently cooled, however, so that it may not rise over 25,000 feet.

Some of the principles which O'Brien used in his analysis should be stressed:

1. It appears that 1.5% of the charge energy goes into the production of waves.

2. For charges fired in very deep water: $H_oR_o = 30\ W^{1/2}$ (Here H_o is the maximum wave height from crest to trough in feet; R_o is the horizontal distance in feet; and W is the charge weight in pounds); the wave-length, $L_o = 16\ W^{1/4}$ feet; the wave velocity is $C_o = 9.0\ W^{1/8}$ feet-second and the group velocity is half as much.

3. From the "Seal" experiments it appears that when shots are fired in water of depth, D(feet), if L_o is the wave-length that the wave would have it fired in deep water and if H, R, and L are the wave-height, distance and wave-length which they actually have:

D/L_o	0.0	0.22	0.28	0.50	0.80
HR/H_oL_o	0.0	0.48	0.40	0.80	1.00
L/L_o	0.0	0.69	0.63	0.89	1.00

III. Formation of Tidal Waves.

There is some concern over the possibilities of the explosions setting up tidal waves which over-run the islands, etc. According to Comdr. Roger [redacted]

[redacted]

Revelle there are two ways that this might occur:

1) Underwater landslide. The underwater rock structure of the atoll is very steep (of the order of 30 degrees) as it drops off from the islands to the deep water. There has never been an earthquake in this region and there is probably a lot of coral shale which might easily be shaken loose to form a landslide. If this should occur, a tidal wave would be formed. Apparently the tide would rise so slowly even in the vicinity of the landslides that it would not represent much of a hazard for the personnel in boats but might over-run the shore installations.

2) Seiches. The atomic bomb explosion might set up characteristic vibrations of the water in the lagoon which would swish to and fro in the form of a tidal wave. From the dimensions of the lagoon and the placement of the explosion it appears that the most likely frequency of the seiche is between 4 1/2 and 5 minutes. Since the phenomena depends on resonance, the amplitude is very sensitive to the exact position of the explosion. Because of this sensitivity the height of the tidal wave is unpredictable. If a seiche of large amplitude were formed, it would increase the likelihood of an underwater landslide.

[redacted]

[redacted]

B-15 REPORT VIII-1

FORMATION AND RISE OF THE SMOKE COLUMN

The methods which we have used in considering the formation and rise of the smoke column after the explosion are based on a rough treatment developed by G. I. Taylor (see report LA-236 and LA-270). Previously we have neglected the staration of the air in the smoke column and as a result our predictions of the maximum height of rise have been low. For the purpose of the Navy Crossroads Test we propose to integrate the equations stepwise as the smoke column rises through the true atmosphere.

The exact pattern of turbulent convection above a steady line source of heat (such as a long hot wire) has been determined by Schmidt. The derivation, however, is too complicated to apply to other examples such as a steady point source of heat. For this reason, G. I. Taylor developed an approximate method which agrees with Schmidt's results in the case of the steady line source of heat and which may be applied to much more complicated problems. Taylor makes the following assumptions:

1. The turbulent heated air column is sharply defined. Within this column the air rises with a velocity, u, which is a function of altitude but not a function of horizontal distance.

2. The rate of taking air into the turbulent column is proportional to the velocity of rise of the air within the column at the height in question. That is, the volume of air taken into the smoke column in an element of height, δh, in unit time is $\alpha u A$ where A is the cross-sectional area of the column and α is a constant. Empirically Taylor finds that $\alpha = 0.2$.

[redacted]

3. The problems are further specified by including the usual equations of conservation of energy and the equation of motion. The equation of motion is just the Law of Archimedes for the static lift of a gas balloon, the lifting force is equal to the difference between the weight of the air within the column and the outside air which it displaces.

We are interested in a somewhat different problem. After the explosion, shock waves pass out through the air dissipating energy as they progress. The air through which these shock waves pass is left heated. Approximately 50% of the energy of the explosion is thus dissipated in the form of heat by the time that the shock pressure is down to 10 atmospheres. Actually most of the energy goes into low grade heating of from 10°C to 100°C. After the shock waves have disappeared, the pressure returns to one atmosphere and we are left with the starting condition of a sphere of radius, R_o, to which has been added the energy, E_o, equal to approximately half the energy of the explosion. For an explosion where the energy released is equivalent to 20,000 tons of TNT we have

$$E_o = 4.2 \times 10^{20} \text{ ergs} \quad , \quad R_o = 300 \text{ yards}$$

In the Cross-Roads Test where the explosion takes place over water, we further assume that the initial sphere is saturated with water vapor. These conditions are somewhat different from the steady state heating problems which Taylor previously considered. However, for lack of better information or mathematical skill we apply essentially the same procedures. It is necessary to make one additional assumption regarding the shape of the smoke puff. This is:

4. Instead of the smoke rising in a column we idealize the situation

[redacted]

by assuming that the heated air is originally in the shape of a sphere and that it remains spherical as it rises and expands. A further idealization consists in assuming that the temperature of the air and the upward velocity is constant throughout the sphere.

The formation and growth of the smoke puff can be followed stepwise in the following fashion. In the interval of time, δt, the puff rises in height by $\delta h = \delta t/u$. The density of the outside air at the height h is $\rho_o(h)$ so that the increase in mass of the puff in this interval of time is

$$\delta M = .2u(4\pi R^2)\,\rho_o(h)\,\delta t$$

The moisture content of the outside air is known as a function of altitude so that we know the amount of moisture which is taken into the puff in each interval of time. Let M_a be the mass of dry air in the puff and M_w be the mass of moisture in the puff. From energy considerations we can estimate the change in temperature of the puff as it (a) takes in a known mass of air of known composition at the outside temperature characteristic of the altitude and (b) expands from p(h) to p(h)(dp/dh)h. Knowing the new temperature and the new pressure (together with the new composition) we can get the new density within the puff from the equation of state of air. Then from the new mass of air and density in the puff, we get the new radius of the puff. The new velocity of rise of the puff can then be computed from the Archimedes lift using the new density inside and outside of the puff. Thus the growth and rise of the puff may be followed stepwise.

[redacted]

61

[redacted]

B-15 REPORT X -1

CONTAMINATION OF THE WATER AND SHIPS

The region under the bomb will be contaminated due to two causes:

1. The deposition of fission products by direct action of the blast.

2. The formation of radioactive substances by neutron absorption.

It is believed that the first will lead to more radiation than the second. This report contains some considerations of Dr. W. G. Penney as to the magnitude of the γ-radiation above the water due to the fission products and its time dependence. The neutron induced contamination is considered in the following report.

[redacted]

[redacted]

Radiation Hazards

The Turbulent Diffusion of the Radioactive Products in the Sea

W. G. Penney

The purpose of this memorandum is to demonstrate that the radiation hazards will be very considerably mitigated by the turbulent diffusion of the products down into the water. The radiation hazards in Shot A may be anticipated small after four hours and may even be tolerable for short times at 2 hours. Even in Shot B, they may be small in 12 hours except possibly for ships near in, and down wind.

The danger from radioactivity may be divided into two classes:

(1) Those arising from the fission products
(2) Those arising from secondary radioactive products induced in the material structure of the ships.

Evidence from the Trinity experiment, and from measurements in Hiroshima and Nagasaki, make it practically certain that (2) will be below the significant level for both shots.

With regard to (1) in Shot A, two possibilities must be considered. The first is that the flame region containing fission products will extend over at least one ship and contaminate it by actual deposition. Here it may be stated that ships which are this close will in all probability sink. Therefore it is unlikely that any ship which still floats will be contaminated by primary products. The second represents the only serious possibility and is that the fission products will condense on the surface of the sea directly, or be condensed on droplets which return to the surface of the sea.

With regard to (1) in Shot B, three possibilities must be considered. The first is direct contamination of a ship by the flame zone; contamination in this way of a ship which does not sink is very small. The second is contamination of a ship by water drops containing radioactive products falling on the ship. This appears a serious possibility for ships near-in down wind. Some trouble may be expected for these ships. The third is the spreading of the fission products over the surface and throughout the volume of the sea within about 1500 feet of the explosion center.

Shot A

We may suppose that in this shot the products are initially spread uniformly over a certain area, estimated roughly at 1000 feet radius. If the products did not move, the radiation density above the water surface in this area would be given by the accepted formula, provided by Weisskopf

$$R(\text{per hour}) = \frac{3200}{T(\text{hours})} \; \frac{n(\text{kilotons})}{m(\text{sq miles})}$$

[redacted]

[redacted]

where P is the fraction of the fission products actually deposited, n is the energy of the explosion in kilotons, and m square miles in the area over which the products are spread.

Just what the true value of P will be is to some extent a matter of speculation. However, the writer believes with some confidence that P will not exceed 0.001. This value is about one-tenth that found at Trinity. Having regard to the very different heights of burst (600 feet or more as against 100 feet) the value 0,001 is considered a very safe maximum value to assume. Then

$$R(\text{per hour}) = \frac{4000}{T}$$

where T is in hours. This formula may well overestimate R by a factor 10.

Clearly, if the products remained fixed on the surface, it would not be safe to venture into the central area even for a few minutes until two or three days after the explosion have passed.

There are, however, at least two further factors that will considerably reduce the radiation hazards. The first is the turbulent diffusion of the fission products down into the water, where their effect is much reduced, or even completely removed. The second is the carrying away of the products by the tide. The second factor is not altogether material, because the radiation hazard will still remain in the water, although its center will have moved.

For simplicity, consider only diffusion downwards from the surface. The density of radioactive products at depth Y at time T will be

$$R(T)\ (\pi KT)^{-1/2} e^{-Y^2/4KT}$$

where R(T) is the radiation density at the surface assuming the products have not moved, and K is the eddy coefficient of diffusion.

Let λ be the mean free path of the α-radiation in water (actually λ is about 30 cm). Then the radiation density above the surface of the water is

$$\phi = R(T)\ (\pi KT)^{-1/2} \int_0^{\infty} e^{-Y/\lambda} \cdot e^{-Y^2/4KT}\, dY$$

Evaluating this expression, we get

$$n = \frac{\phi}{R(T)} = e\ \frac{KT}{\lambda^2}\ 1 - \Phi\left(\frac{\sqrt{2KT}}{\lambda}\right)$$

where $\Phi (x) = \frac{1}{\sqrt{2\pi}} \int_x^{x} e^{-x^2/2}\, dx$

and is the probability integral.

[redacted]

[redacted]

Thus η represents the reduction of the radiation density above the surface due to the downward diffusion of the fission products, If $4KT > c^2$, then a good approximation to η is

$$\eta = \frac{c}{\sqrt{\pi KT}}$$

The larger the value of T, the better in this approximation.

The question now arises as to the proper value of K. The larger K, the more rapid the diffusion, and the less the value of η. Referring to "The Oceans" by Sverdrup, Johnson and Fleming, the least value of K ever measured was in Danish Waters at depths 0-15 m. The value of K ranged from 0.02 up to 0.6. These waters are of great stability and moderate currents. The water is greatly stabilized by a saline density gradient, and the surface water is nearly fresh. A much more comparable case for our purposes is found in the Bay of Biscay. Here the depth of water was 100 meters and the values of K range from 2 to 16. It is therefore considered that K = 1 is definitely on the low side, that K = 4 is the most probable value, and K = 8 is slightly on the high side. Substituting these values, we find the following values of η at times T hours -

K = 1		K = 4		K = 8	
T	η	T	η	T	η
0.25	0.427	0.125	0.337	0.175	0.24
0.50	0.337	0.35	0.24	0.25	0.20
1.4	0.24	0.50	0.20	0.50	0.14
2.0	0.20	1.00	0.14	1.00	0.10
4.0	0.14	2.000	0.10	2.00	0.07
8.0	0.10	4.00	0.07	4.00	0.25

It will be seen that the effect of the eddy diffusion at two hours is to reduce the radioactivity by a factor 10. At four hours, the factor is 15 - 20.

Accepting the pessimistic value that 0.001 of the fission products is deposited on the sea over a circle of radius 1000 feet, the R values above this region, as it moves with the tide will be -

[redacted]

[redacted]

T hours	1	2	4	10
R per hour	560	200	70	18

These are considered safe estimates; the actual values may well be less even by a factor as much as 10.

Shot B

The radiation hazards in this shot are of course much more severe than in Shot A. The main factors that control the time at which the central region becomes safe for entry are the tide, and the splashing of radioactive water over the ships which do not sink.

The following are considered reasonable guesses; no evidence exists on which to formulate better calculations:

Initially, the fission products will be distributed uniformly through a cylinder of radius 1500 feet, going to the bottom. About 5% of the products will be found in the water. Turbulent diffusion does not help reduce the radiation above the water, except to a very slight degree by spreading the region. This spread however is negligible.

The radiation density above the water, allowing for the mean free path of the γ-rays in water is

$$R(\text{per hour}) = \frac{500}{T}$$

Even after 10 hours, the radiation is down only to 50 R per hour over the water. The radiation in the ships is unpredictable.

[redacted]

[redacted]

GROUP B-15 REPORT X-1-A

Corrections to Penney's Report, "The Turbulent Diffusion of the Radioactive Products in the Sea" which was Included in the Cross-Roads Handbook as B-15 Report X-1

There are two numerical mistakes in Penney's calculations which make the radioactivity above the sea-water after the first shot about 13.3 times too large.

The first mistake is in the numerical coefficient of the equation at the bottom of his first page which should read:

$$R(\text{per hour}) = P\,\frac{1690}{T(\text{hours})}\,\frac{n(\text{kilotons})}{m(\text{sq. miles})}$$

The coefficient 1690 corresponds to a height of 3 feet above the surface of the water. In using 3200 instead of 1690, Penney overestimated the radioactivity by a factor of 2.

The second numerical mistake arose when Penney substituted $P = .001$, $n = 20$, $m = (1/5.28)^2 3.1416 = .1127$ in the above equation. Instead of getting $R(\text{per hour}) = 4000/T$, he should get:

$$R(\text{per hour}) = 300/T$$

The net result is that his final table for the radioactivity above the sea-water after the first shot (taking into account the vertical diffusion) should read:

T(hours)	1	2	4	10
R(per hour)	42	15	5.25	1.35

Actually we believe that it would have been slightly better to have supposed that in the first shot 0.2% of the fission products were deposited within a radius of 1500 feet instead of 0.1% within 1000 feet. However, this would make

[redacted]

47

[redacted]

the R (per hour) smaller than the above values by the factor 0.889 which is an inappreciable change.

Penney must have made some sort of numerical mistake in his estimate of the radioactivity above the sea-water after the second shot. Instead of obtaining R (per hour) = 500/T , he should have gotten:

R (per hour) = 28/T

Thus the radioactivity above the sea water following the second shot should not be bad for more than a few hours.

[redacted]

DECLASSIFIED

[redacted]

ARCHIVES OF HEADQUARTERS AAF WEATHER SERVICE

WEATHER DURING MAY IN THE BIKINI AREA

REPORT NO. 1035

[redacted]

Prepared by Headquarters AAF Weather Service

February 1946

69

[redacted]

WEATHER DURING MAY IN THE BIKINI AREA

The following description of the climate in the area of Bikini Atoll is based on observations taken by the AAF Weather Service at Kwajalein Atoll during May 1944 and 1945. Because the period of record is short, conclusions based on the data are likely to be misleading. Therefore, a great deal of care should be used in making any interpretations of the information.

Cloudiness

Cloudiness over the atoll is considerably greater than that reported over the adjacent ocean area. During the period of record, clear skies were observed on only one or two days at Kwajalein. Scattered clouds (0.1 through 0.5 cloud cover) were most frequent. The distribution of cloudiness at Kwajalein is shown in Table 1.

Table 1.--Average Sky Condition during May at Kwajalein

Clear (<0.1 cloud cover)	0.5%
Scattered (0.1 through 0.5 cloud cover)	41.9
Hi. Brkn. (0.5 through 0.9 cloud cover) or Overcast (with ≥0.5 low clouds)	31.7
Low Broken (≥0.5,<0.9 cloud cover)	18.0
Low Overcast (≥0.9 cloud cover)	7.9

The average diurnal variation of cloudiness during the period of record for May is shown in Figure 1. Cloudiness was least during the night and early morning and increased during the warm daylight hours. The period of greatest cloudiness was between 0700 and 1800 local time. The rare occurrences of clear skies were observed late at night and in the early morning.

[redacted]

[redacted]

Ceilings

Ceilings were generally higher than 950 feet during May; they were lower than 2,050 feet on only 8.1 percent of the obersvations. On more than 74 percent of the observations, ceilings were above 9,750 feet. The percentage frequency during May of ceiling height is shown in Table 2.

Table 2.--Average Distribution of Ceiling Height during May at Kwajalein

0--450 feet	0.0%
0--950	0.3
0-2050	7.8
0-3050	15.4
0-5250	21.7
0-9750	25.8
Over 9750	74.2

Visibility

During May visibility was always excellent at Kwajalein. On less than 1 percent of the observations, it was below 3 miles; on 6.1 percent less than 10 miles. The percentage frequency of visibility limits is shown in Table 3.

Table 3.--Average Distribution of Visibility Limits during May at Kwajalein

0 to 1/8 Mi.	0.0%
0 to 1/4	0.1
0 to 1/2	0.1
0 to 3/4	0.1
0 to 2 1/4	0.9
0 to 2 1/2	0.9
0 to 6	4.1
0 to 9	6.1
10 and Over	93.9

Poorest visibilities occurred during the afternoon and evening hours. The hourly distribution of visibility limits is shown in Figure 3. Fog is rarely observed and did not occur during May 1944 and 1945.

[redacted]

[redacted]

Precipitation

Winter and spring correspond to the dry season, so that precipitation from December through May is at a minimum. During May 1944, the mean precipitation amounted to 4.57 inches, and there were 18 days on which amounts of .01 inch or more were recorded.

Thunderstorms were very infrequent; only four were recorded during February 1944 through October 1945 at Kwajalein. None were recorded during May.

Temperature

The range of temperature in the Bikini area is very small, and the variation of the monthly means during the course of the year is less than the diurnal range. Temperature values for the period of record at Kwajalein are shown in Table 4.

Table 4.--Temperature (°F.) during May at Kwajalein

Mean daily temperature	82.3°
Mean daily maximum temperature	87.4°
Mean daily minimum temperature	77.1°
Absolute maximum temperature	90°
Absolute minimum temperature	71°

Winds

During May winds at Kwajalein were generally from an easterly direction. They were moderate to fresh (13 through 24 m.p.h.) on 78 percent of the observations, and light to gentle (less than 13 m.p.h.) on less than 19 percent of the observations. Winds of force greater than 32 m.p.h. occurred on less than 0.1 percent of the observations during May. The distribution by direction and force is shown in Table 5.

[redacted]

[redacted]

Table 5.--Percentage Frequency of Wind Direction by Velocity Groups during May at Kwajelein

	1-3 m.p.h.	4-12 m.p.h.	13-24 m.p.h.	25-31 m.p.h.	32-46 m.p.h.	46 m.p.h.
N						
NNE		0.1				
NE		0.3	7.8	0.5		
ENE	0.1	2.6	24.2	9.5		
E		7.3	26.8	1.5	0.1	
ESE	0.1	6.2	17.7	0.6		
SE	0.1	1.1	1.2	0.2		
SSE		0.5	0.4			
S		0.1				
SSW						
SW						
WSW						
W						
WNW						
NW						
NNW						
Calm						
Total	0.3	18.2	78.1	3.3	0.1	

Typhoons

Typhoons are uncommon in the Marshall Islands, but they are not unknown. For example, the atoll of Ailinglapalap was devastated by a typhoon in the autumn of 1874. Typhoon data for this area, however, are scarce, and they may be more severe storms in the region than are evident from available sources of information.

Intertropical Front

In the longitude of the Marshalls the mean position of the intertropical front is still south of the equator during May.

Height of the Tropopause

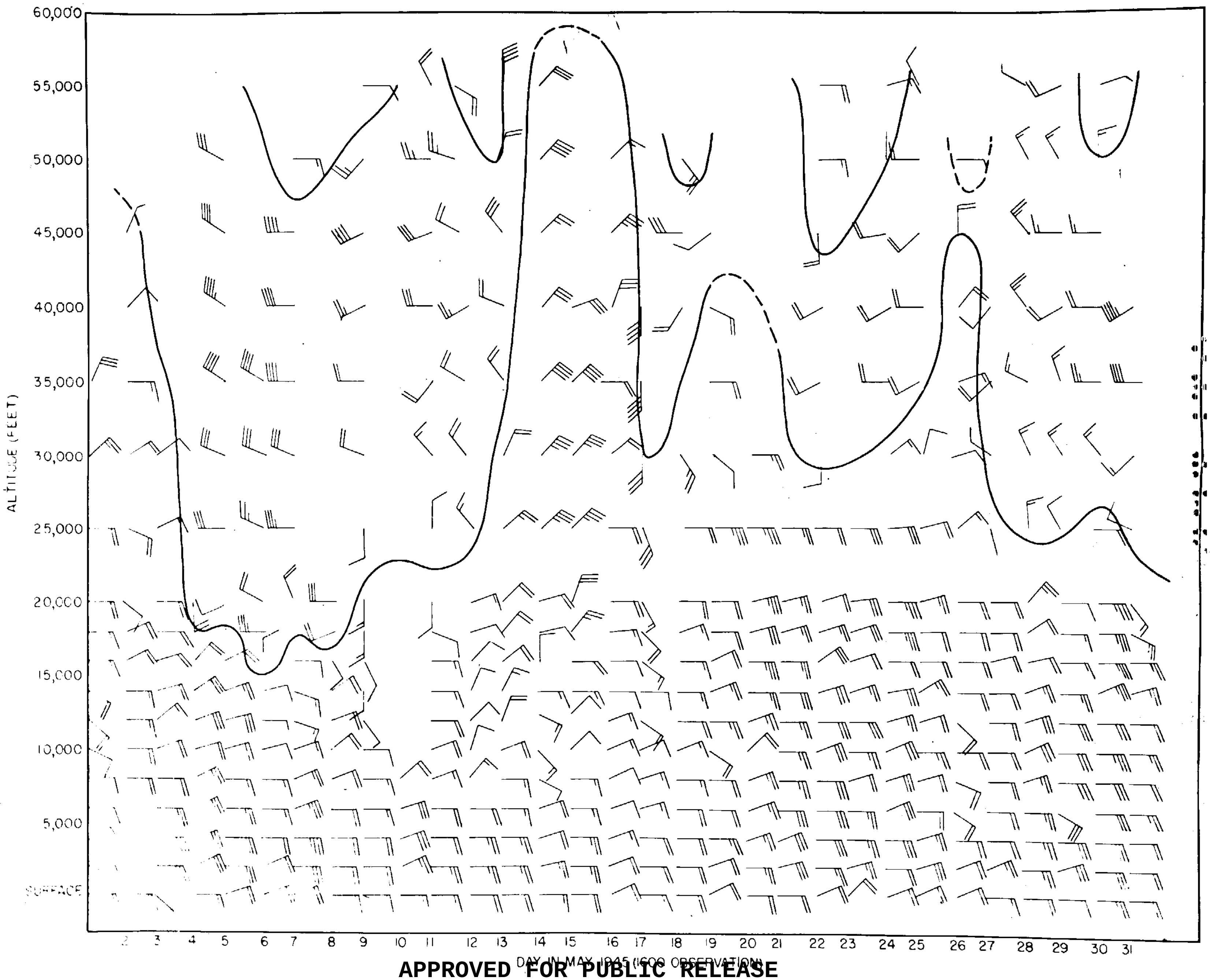
Available records of radiosonde ascents in the Bikini area do not reach sufficient heights to give an average value of the height of the tropopause. An

[redacted]

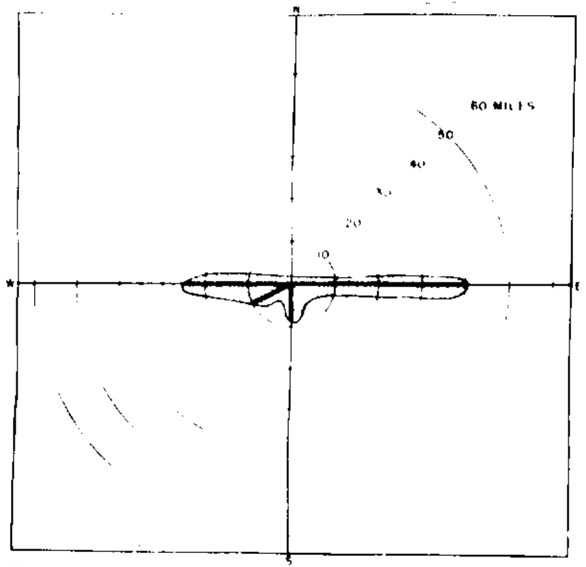
estimate may be obtained, however, from ascents at Batavia, N.E.I., where the height of the tropopause averages between 17 and 19 kilometers.

[redacted]

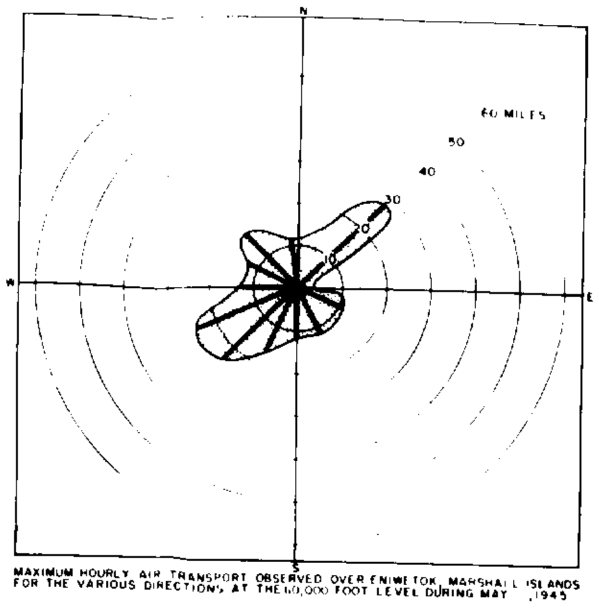
WIND OBSERVATIONS ON ENIWETOK MAY 1945
(WIND SPEED- EACH BARB 10 M.P.H.)



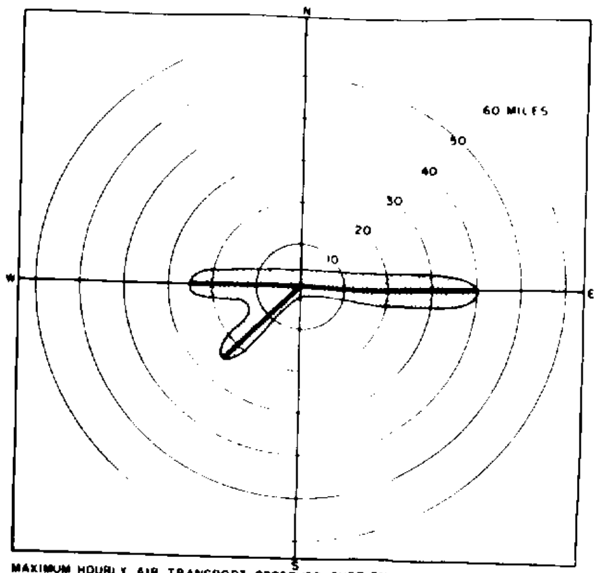
MAXIMUM HOURLY AIR TRANSPORT BY LEVELS (0-65000 FT.) OVER ENIWETOK, MARSHALL ISLANDS DURING MAY 1945



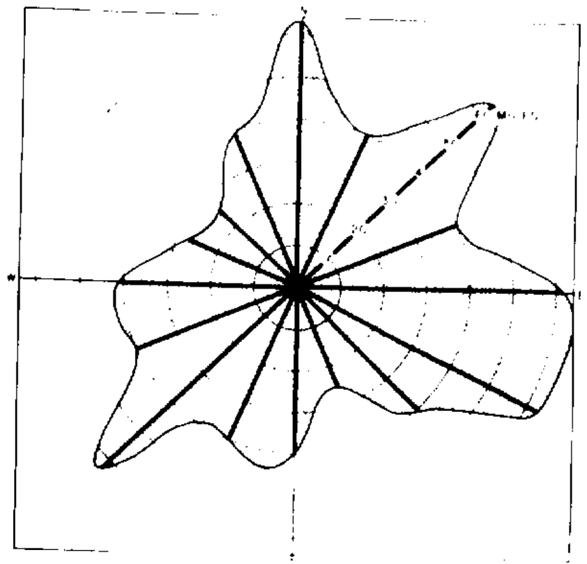
PREVAILING HOURLY AIR TRANSPORT (AVERAGE) FOR LEVELS 0-65000 FT OVER ENIWETOK, MARSHALL ISLANDS DURING MAY , 1945



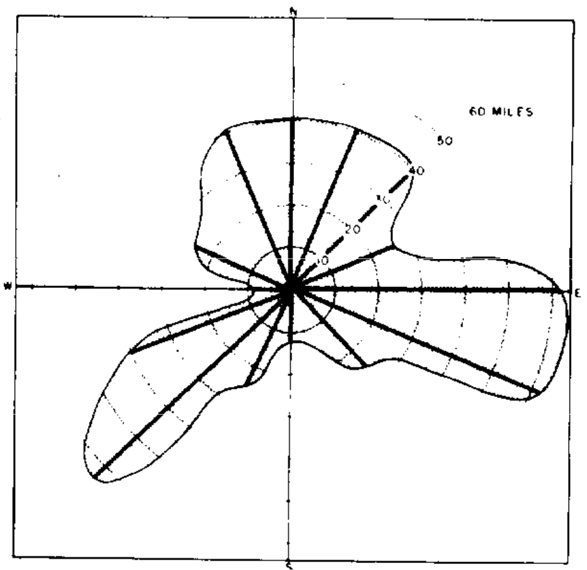
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 60,000 FOOT LEVEL DURING MAY , 1945



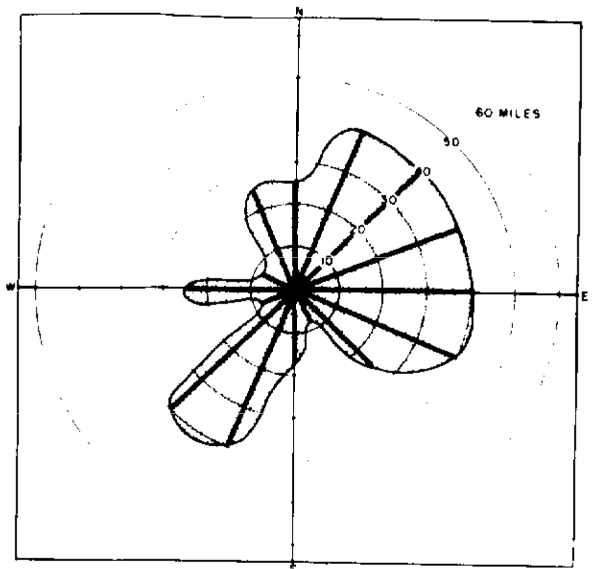
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 65,000 FOOT LEVEL DURING MAY , 1945



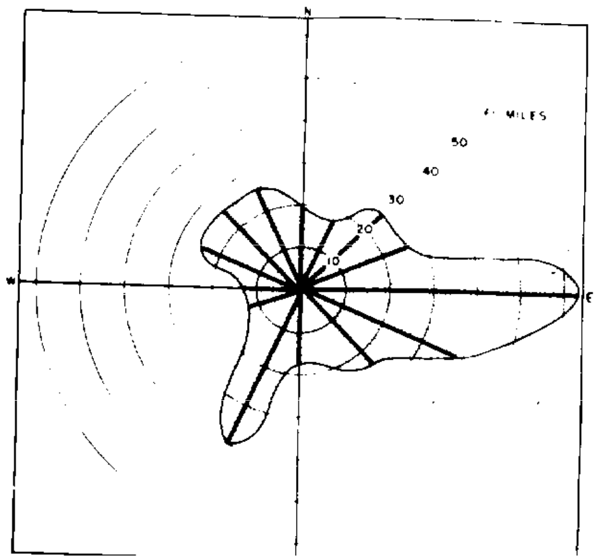
MAXIMUM HOURLY DISPLACEMENT IN MILES FOR ALL DIRECTIONS (CONSIDERS ALL LEVELS 0-65,000) OVER ENIWETOK, MAY 1945.



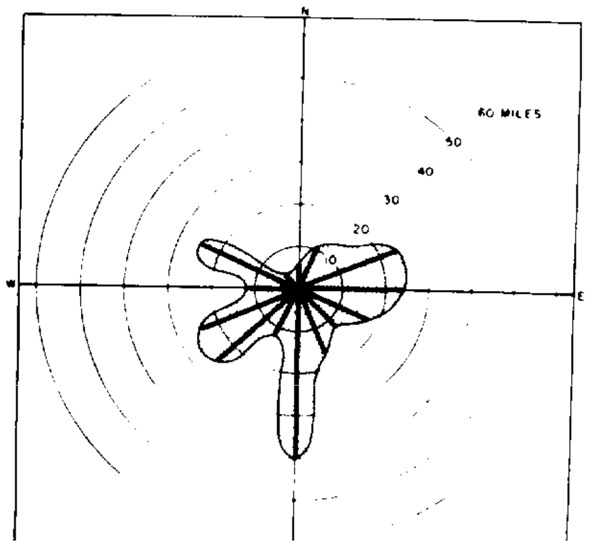
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 40,000 FOOT LEVEL DURING MAY , 1945



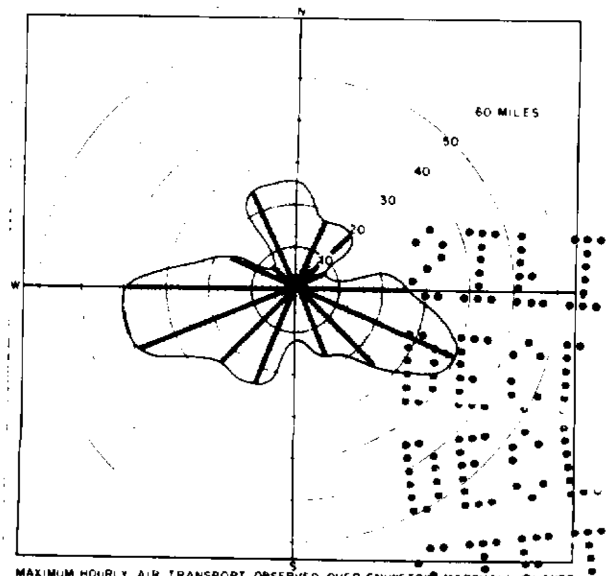
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 45,000 FOOT LEVEL DURING MAY , 1945



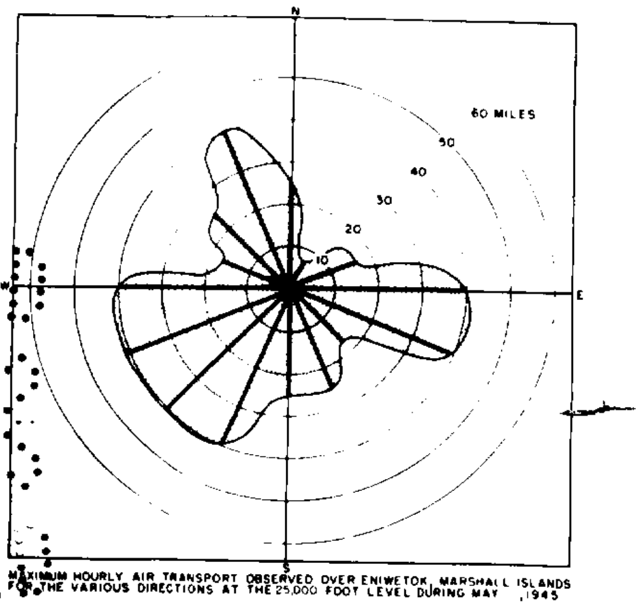
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 50,000 FOOT LEVEL DURING MAY , 1945



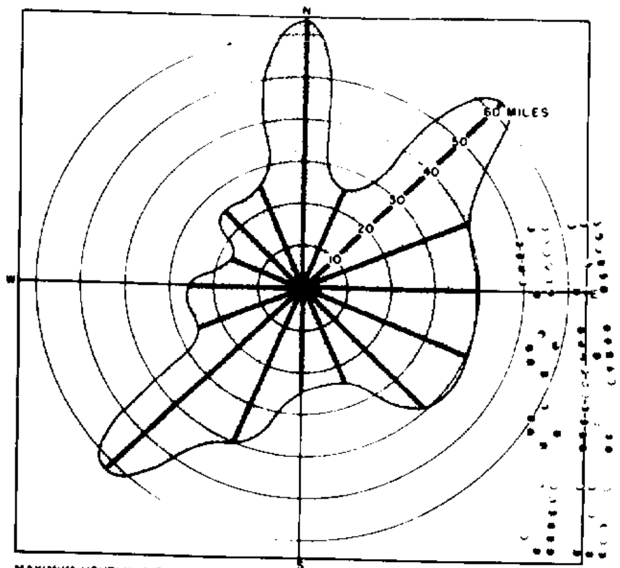
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE [illegible] FOOT LEVEL DURING MAY , 1945



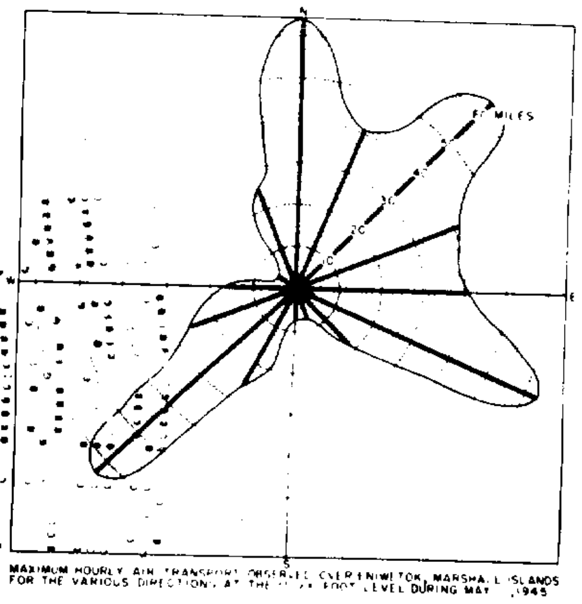
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 20,000 FOOT LEVEL DURING MAY , 1945



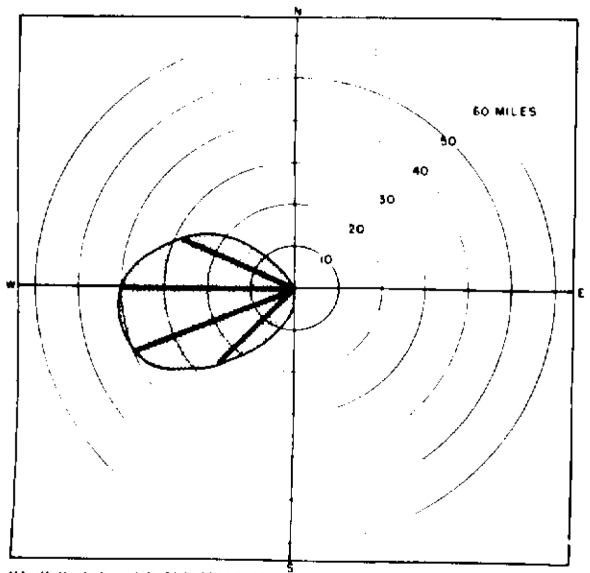
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 25,000 FOOT LEVEL DURING MAY , 1945



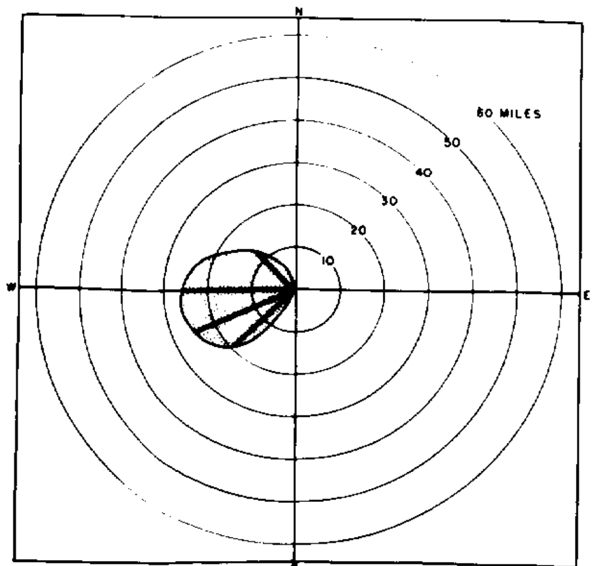
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 30,000 FOOT LEVEL DURING MAY , 1945



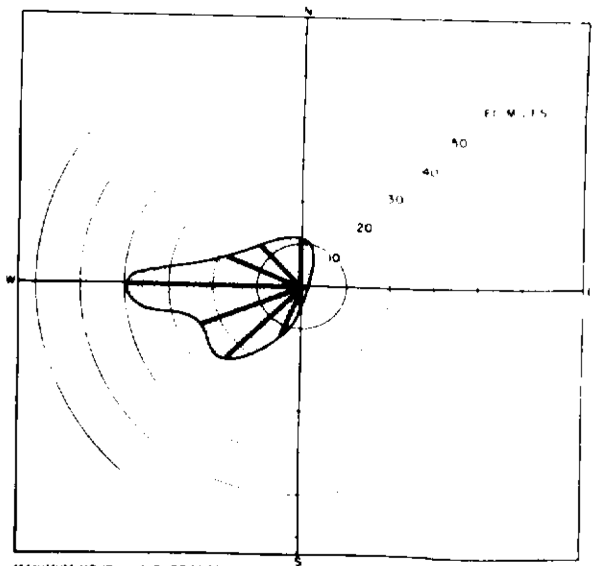
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE [illegible] FOOT LEVEL DURING MAY , 1945



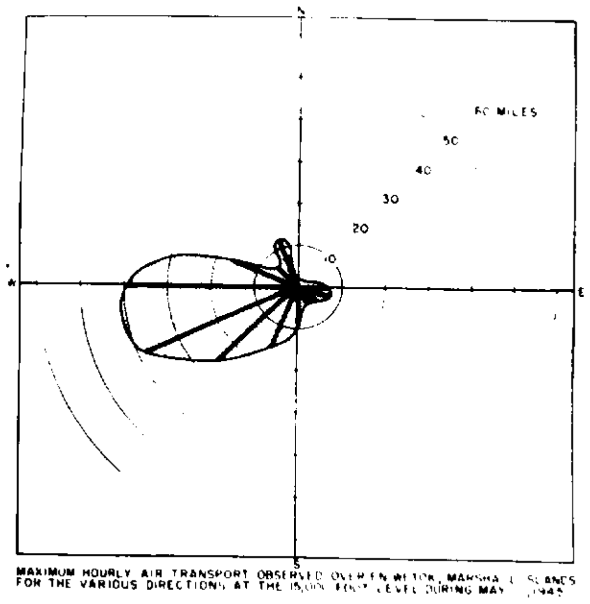
MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 5,000 FOOT LEVEL DURING MAY , 1945



MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE SURFACE LEVEL DURING MAY , 1945



MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 10,000 FOOT LEVEL DURING MAY , 1945



MAXIMUM HOURLY AIR TRANSPORT OBSERVED OVER ENIWETOK, MARSHALL ISLANDS FOR THE VARIOUS DIRECTIONS AT THE 15,000 FOOT LEVEL DURING MAY , 1945

76

[redacted]

PUBLICATIONS OF HEADQUARTERS AAF WEATHER SERVICE

WEATHER DURING JUNE AND JULY IN THE BIKINI AREA

REPORT NO. 1015
(Continued)

Prepared by Headquarters AAF Weather Service

February 1946

[redacted]

WEATHER DURING JUNE AND JULY IN THE BIKINI AREA

[redacted]

In this report, the description of the weather in the area of Bikini Atoll is continued. As in the report for May, data are based on a two-year record of observations taken by the AAF Weather Service at Kwajalein Atoll during June and July of 1944 and 1945. Because the period of record is short, conclusions based on these data are likely to be misleading. Therefore, a great deal of care should be used in making any interpretation of the information.

WEATHER CONDITIONS DURING JUNE

Cloudiness

Clear skies were practically nonexistent during June; the few times observed occurred during the night hours. The frequency of scattered clouds decreased in June, and the frequency of high broken or overcast conditions increased to become the dominant type of sky cover. The distribution of cloudiness at Kwajalein is shown in Table 6.

Table 6.--Average Sky Condition during June at Kwajalein.

Clear ($<$0.1 cloud cover)	0.3%
Scattered (0.1 through 0.5 cloud cover)	33.1
Hi. Brkn. (0.5 through 0.9 cloud cover) or overcast (with $\geq$ 0.5 low clouds)	49.2
Low broken (0.5 through 0.9 cloud cover)	14.5
Low overcast ($>$0.9 cloud cover)	2.9

The average diurnal variation of cloudiness during the period of record for June is shown in Figure 4. The greatest frequency of scattered clouds was observed during the night and early morning hours. High broken or overcast skies occurred from 0900 through 2000 local time. The few instances of clear skies were observed during the hours of 2100 through 0100 local time.

[redacted]

[redacted]

Ceiling

During June ceilings less than 951 feet were observed only once; they were lower than 2,051 feet on only 6.3 percent of the observations. On more than 82 percent of the observations, ceilings were above 9.750 feet. The percentage frequency during june of ceiling heights is shown in Table 7.

Table 7.--Average Distribution of Ceiling Height during June at Kwajalein.

0-450 feet	0.0%
0-950 "	0.1
0-2050 "	6.3
0-3050 "	12.5
0-5250 "	14.4
0-9750 "	17.3
Over 9750 "	82.7

In Figure 5 are shown the hourly frequencies of various ceiling heights at Kwajalein during the period of record.

Visibility

Visibility was less than 3 miles during June on only 0.4 percent of the observations. Visibility was generally excellent, being over 10 miles on more than 96 percent of the observations. The percentage frequency of visibility limits is shown in Table 8.

Table 8.--Average Distribution of Visibility Limits during June at Kwajalein.

0-1/8 mi.	0.1%
0-1/4 "	9.1
0-1/2 "	0.2
0-3/4 "	0.2
0-2 1/4"	0.4
0-2 1/2"	0.4
0-6 "	2.8
0-9 "	3.5
10 and over	96.5

Occurrences of poor visibility were scattered throughout the day and were probably caused by heavy rain showers. The hourly distribution of visibility is shown in Figure 6. Fog is rarely observed and did not occur during June 1944 and 1945.

[redacted]

[redacted] 79

Precipitation

Although June is in the rainy season, the average precipitation of 3.00 inches during June 1944 and 1945 was less than the average for May. There were 16 days on which precipitation amounts of .01 inch or more were recorded.

Of the 4 thunderstorms recorded during the period of February 1944 through October 1945 at Kwajalein, 2 of them occurred in June.

Temperature

The variation in temperature from month to month is very small, and during May, June, and July, there is little change. Temperature values for the period of record at Kwajalein are shown in Table 9.

Table 9.--Temperature (°F.) during May at Kwajalein.

Mean daily temperature	82.4°
Mean daily maximum	87.3
Mean daily minimum	77.2
Absolute maximum	90
Absolute minimum	73

Winds

Surface winds at Kwajalein during June continued from an easterly direction. On 83 percent of the observations, they were moderate to fresh (13 through 24 m.p.h.) and on 15 percent of the observations, light to gentle (less than 13 m.p.h.). Winds greater than 32 m.p.h. occurred only twice during the period of record for June. The distribution by direction and force is shown in Table 10.

[redacted]

[redacted]

Table 10.--Percentage Frequency of Wind Direction by Velocity Groups during June at Kwajalein.

	1-3 m.p.h.	4-12 m.p.h.	13-24 m.p.h.	25-31 m.p.h.	32-46 m.p.h.	46 m.p.h.
N						
NNE			0.1			
NE		0.8	4.6	0.1		
ENE		4.6	32.3	0.5		
E		5.0	33.6	0.9	*	
ESE		3.9	11.6	0.2	*	
SE		0.4	0.8			
SSE		0.1	0.1			
S						
SSW						
SW		0.1				
WSW						
W						
WNW						
NW	0.1					
NNW						
CALM						0.1

* 0.1%.

Typhoons

Typhoon data for the Bikini area is scarce, but tropical storms are not unknown. During the period of record for June, apparently there were no severe storms since the strongest winds recorded were between 32 and 46 m.p.h. and these on only two occasions.

Intertropical Front

During June the intertropical front in the longitude of the Marshalls begins to move northward, and its mean position lies approximately on the Equator. The location of the front during June of 1945 at 165° E. longitude varied from 3° S. latitude to 4° N. latitude with the mean position lying between 1° and 3° N. latitude.

Height of the tropopause

There is little change in the height of the tropopause during June. From ascents at Batavia, N.E.I., it is estimated that the height of the tropopause averages between 17 and 19 kilometers.

[redacted]

[redacted]

WEATHER CONDITIONS DURING JULY

Cloudiness

During the period of record for July there were no occurrences of clear skies. High broken clouds or overcast skies were the most frequently observed conditions; scattered clouds were next, their frequency having increased slightly over June. The distribution of cloudiness at Kwajalein is shown in Table 11.

Table 11.--Average Sky Condition During July at Kwajalein

Clear (<0.1 cloud cover)	0.0%
Scattered (0.1 through 0.5 cloud cover)	33.6
Hi. Brkn. (0.5 through 0.9 cloud cover) or overcast (with 0.5 low clouds)	45.5
Low Broken (0.5 through 0.9 cloud cover)	14.8
Low Overcast (>0.9 cloud cover)	6.1

The average diurnal variation of cloudiness during the period of record for July is shown in Figure 7. As in the previous months, the greatest frequency of scattered cloudiness occurred during the night and early morning hours with cloud amounts increasing to broken or overcast during the day.

Ceiling

Ceilings less than 951 feet were observed three times during July 1944 and 1945, or on less than 0.2 percent of the observations. They were less than 2,051 feet on 9.4 percent of the observations, or almost 3 percent more frequently than in the preceding month. Ceilings were above 9,750 feet on 79 percent of the observations. The percentage frequency during July of ceiling heights is shown in Table 12.

Table 12.--Average Distribution of Ceiling Height during July at Kwajalein.

0 -- 450 feet	0.1%
0 -- 950 "	0.2
0 -- 2050 "	9.4
0 -- 3050 "	15.3
0 -- 5250 "	17.3
0 -- 9750 "	20.9
Over 9750 "	79.1

[redacted]

In Figure 8 are shown the hourly frequencies of various ceiling heights at Kwajalein during the period of record.

Visibility

Visibilities of less than 3 miles occurred on 0.8 percent of the observations during July 1944 and 1945, heavy rain showers probably being the obstruction. Generally, however, visibilities were excellent being over 10 miles on 93.3 percent of the observations. The percentage frequency of visibility limits is shown in Table 13.

Table 13.--Average Distribution of Visibility Limits during July at Kwajalein.

0 -- 1/8 Mi.	0.0%
0 -- 1/4 "	0.1
0 -- 1/2 "	0.3
0 -- 3/4 "	0.3
0 -- 2 1/4"	0.8
0 -- 2 1/2"	0.8
0 -- 6 "	4.7
0 -- 9 "	6.7
10 and over	93.3

Occurrences of poor visibility were scattered throughout the day, as is evident from Figure 9 which shows the hourly distribution of visibility. Fog was not observed during July of 1944 and 1945.

Precipitation

Both the number of days with precipitation and the mean monthly amount of precipitation increased during July. The average amount of rain for the period of record was 5.94 inches, and there were 28.5 days on which precipitation amounted to .01 inch or more.

Temperature

There was little change in temperature from June to July. Temperature values for the period of record at Kwajalein are shown in Table 14.

[redacted]

Table 14.--Temperature (°F.) during July at Kwajalein.

Mean daily temperature	82.1°F.
Mean daily maximum	87.6
Mean daily minimum	76.4
Absolute maximum	92
Absolute minimum	71

Winds

During the period of record for July surface winds maintained their easterly component. However, there were occurrences of winds from all points of the compass during this month. The predominant wind force remained moderate to fresh((13 through 24 m.p.h.) and was recorded on 62.9 percent of the observations. On 35.0 percent of the observations the winds were light to gently (less than 13 m.p.h.). Winds greater than 32 m.p.h. occurred four times during the period of record for July. The distribution by direction and force is shown in Table 15.

Table 15.--Percentage Frequency of Wind Direction by Velocity Groups during July at Kwajalein.

	1-3 m.p.h.	4-12 m.p.h.	13-24 m.p.h.	25-31 m.p.h.	32-46 m.p.h.	47 m.p.h.	
N	0.1	0.1					
NNE		0.3					
NE	0.2	1.9	2.2	0.1			
ENE	0.1	8.4	13.5	0.3	0.1		
E	0.1	11.0	30.0	0.5	0.1		
ESE	0.2	7.3	15.0	0.5	0.1		
SE	0.1	1.4	1.6	0.1			
SSE	0.1	0.9	0.8				
S		0.5	0.2	0.1			
SSW		0.3	0.1	0.1			
SW	0.1	0.8					
WSW		0.1					
W	0.1	0.3					
WNW		0.1					
NW	0.1	0.3					
NNW	0.1						
CALM							0.1
TOTAL	1.3	33.7	62.9	1.7	0.3	-	0.1

Typhoons

During July there were four instances of winds between 32 and 46 m.p.h.,

[redacted]

[redacted]

which were the strongest recorded. Apparently no typhoon occurred in the area.

Intertropical Front

During July the mean position of the intertropical front covers the southern portion of the Marshalls. Although no synoptic data on its position are vailable, it must be assumed that it was located over the Bikini area on occasion during the month.

Height of the Tropopause

Variation in the height of the tropopause during the summer months would be slight; although no data are available for the Bikini area, it is estimated that the height of the tropopause averages between 17 and 19 kilometers. This is based on balloon ascents at Batavia, N.E.I.